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TASKS RELATED TO FIELD IMPLEMENTATION OF HP-GPC, RUTTING AND OTHER STUDIES

Prepared for

Montana Department of Highways

Research Program

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ABSTRACT

Included in this report are sections on the following subjects: a) a description of a statistical model for rutting in asphalt pavement overlays based on asphalt cement and pavement mix parameters; b) discussion of a statistical model for transverse cracking in pavements which have no overlays based on similar parameters; c) a study of the variability in certain asphalt characteristics in nine paving projects constructed in 1988; an evaluation of four 1988 pavements in terms of variability in certain asphalts and mix factors; d) details of the performance of the 1983 Montana Test Sections and a number of other pavements which have been part of an aging study as a prelude to the use of these data in the improvement of pavement performance; e) finally, the results of a survey taken to ascertain the experience of other state and provincial agencies with asphalt modifiers of various types.

SUMMARY AND CONCLUSIONS

This report details the results of several tasks intended to gather data and information in a variety of areas important to the Montana Department of Highways. Because each of these tasks could stand alone, this summary will present each task individually.

Using data gathered for an earlier rutting study, a statistical evaluation of rutting in pavement overlays was undertaken. The modelling efforts involved a multiple regression analysis with rut depth as the dependent variable and a large number of asphalt and mix factors as independent variables. The models obtained emphasize the importance of aggregate gradation variables, penetration (40°) as well as characteristics of the underlying pavement.

The statistical analysis of cracking used portions of the same data base described above to attempt to model contributors to transverse cracking in the Montana Interstate System. Pavements which have not received overlays were studied. Variables found in the model include asphalt content, age, climate region and three aggregate gradation factors. This model is not felt to be entirely satisfactory. Discussion of problems as well as some details about the data are included.

Task 4 involved monitoring the asphalt cements used in eight paving projects constructed during the summer of 1988. Asphalt cements used in the design and construction as well as asphalt extracted from design and construction mixes were analyzed by HP-

GPC. In some cases, the asphalt used in design differed significantly from that used in construction. There was also some variability in the HP-GPC characteristics of the asphalt cement used in construction; the range of %LMS was as little as 1.1 to as much as 9.7%. The thin film oven test sometimes produced widely differing results that did not always reflect the variability of the asphalts from which they were derived. Most important, however, is the variability seen in the asphalts extracted from finished pavements. In six projects, the LMS range is between 0.9 and 1.3%; this range is 2.2% in one project and 10.8% in one project.

Other construction variables were monitored under Task 5. Marshall stabilities were found to be generally higher in the pavement than in design or laboratory prepared samples. However, there are wide ranges in the pavement values. Asphalt content as determined by solvent extraction was found to vary considerably more than when determined by nuclear density instrument. Asphalt content often was significantly different than the design requirement.

Variability in voids content, especially in samples within about 250 square feet, was significant and may make finding relationships with performance very difficult.

The most recent observations of the Montana Test Sections near Big Timber show that the number of transverse cracks continues to increase in many sections, although the increases are tempered by evidence for healing in some sections. However,

some sections, including that for which the asphalt was designed by HP-GPC to resist cracking, continue to give crack-free performance.

Rutting continues to increase in some sections and a few sections underwent significant increases in rut depth during the unusually hot summer of 1988. However, some sections are quite resistant to rutting.

Also included are results from the 1988 survey of aging study projects. These pavements have been followed at intervals since their construction 7 to 12 years ago. Most of the pavements are overlays. Differences in performance are noted. Few significant changes in HP-GPC characteristics of the asphalts have been seen.

Using data derived from studies to date, the possibilities for improving performance are discussed.

Finally, the results of a survey of 30 state and provincial transportation agencies have been tabulated. The agencies report trials of a variety of polymers, fibers and latexes as well as such things as sulfur, carbon black, deicing agents, rubber and Chemcrete. Many trials are in the very early stages and some results are mixed for similar products. A list of references to reports on the construction experience and on some performance observations is included.

TABLE OF CONTENTS

FHWA REPORT DOCUMENTATION		i
DISCLAIMER		ii
ABSTRACT		iii
SUMMARY AND CONCLUSIONS		iv
INTRODUCTION		1
RESULTS AND DISCUSSION		2
Task 1.	Statistical Analysis of Rutting in Overlays on the Montana Interstate System	2
Task 3.	Statistical Analysis of Cracking on the Montana Interstate System	21
Task 4.	Implementation for 1988-1989 Paving Projects	41
Task 5.	Construction Variables	49
Task 7.	Prediction of Pavement Performance	87
Task 8.	New Advances in Asphalt Modification	124

INTRODUCTION

In early 1988, this research group began work on a series of tasks in a project designed to gather data and information in a variety of areas important to the Montana Department of Highways. These tasks range from statistical analysis of data collected under a previous contract, to monitoring variability in selected paving projects to surveying neighboring states and provinces on their use of asphalt additives and modifiers. In fact, these tasks are so diverse that it seems reasonable to treat them as separate entities within the confines of this final report.

A report on Task 1, concerning a statistical analysis of contributors to rutting, was submitted earlier but has been included here as well, in order to gather all the results in one document.

Task 2 involved the design and construction of several Special Provisions paving projects. Although a small amount of very preliminary work was done, these projects were delayed. Therefore, no results from this task are contained in this report.

Task 6 provided an option to the MDOH to have samples tested by HP-GPC and Laboratory Simulation as part of its mix design process. No requests for such services were received, however.

The remaining tasks will be presented individually with brief introductory paragraphs, notes on procedures and discussions of results.

Task 1. Statistical Analysis of Rutting in Overlays in the Montana Interstate System.

Introduction

In work previously reported, (1) a study of rutting on the Interstate highway system in Montana was undertaken. That study involved evaluation of a variety of common physical parameters as well as analyses by HP-GPC and relationships of the results with rut depths actually measured in the pavements. The desired product was a statistical model that would describe rutting throughout the Montana Interstate system.

Efforts to derive a statistical model for all Interstate paving projects was not possible, however. Rutting rates appeared to differ with age and a stable model could not be achieved until pavements that contained overlays were separated from those that did not. The model for non-overlayed pavements has been reported; models for pavements with overlays will be the subject of this report.

The Data

The design of the study, the collection and statistical analysis of data have been described in detail elsewhere (1), and that discussion will not be repeated here. However, a few points specific to the overlayed pavements will be made.

There are two groups of overlay-containing pavements, those with open graded friction courses (OGFC) in addition to the dense graded overlay, and those without OGFC. Open graded friction courses are fairly thin layers, and do not lend themselves to the

testing done on dense graded pavements. No tests were done on OGFC's during this study. The effect of that is, in essence, a tacit assumption that rutting is controlled by the dense graded pavement layers. However, it was noted in (1) that, at four sites, badly stripped dense graded lifts were found under OGFC. Rutting at those sites was negligible at the time of sampling (1986) and had not changed significantly when those sites were resurveyed in 1988. In other words, it is not entirely accurate to assume that rutting is controlled by the dense graded pavement.

With this in mind, it was decided to attempt to derive statistical models by grouping the data for overlay pavements in three ways: 1) the whole set including OGFC-containing pavements as well as those without OGFC; 2) pavements with OGFC only; 3) pavements without OGFC only. This has at least one serious disadvantage in that groups 2 and 3 will have reduced numbers of observations, making modeling more difficult and less reliable. And, in fact, the set containing only overlays without OGFC did prove to be impossible to model. However, the other two data sets did yield reasonable models which will be discussed in the next sections.

Models for Overlays with OGFC

In this section, two possible models for rutting in overlays with OGFC's will be presented. The differences between them as well as the problems leading to a proliferation of models will be discussed.

Model I. Figure 1 contains a plot of rut depth (in mm) versus the age of the overlays. This shows, first, that all of the pavements in the data set, except one, are 6 years old or less, and most are two years old (37 of 62). This has some ramifications for the statistical work in that a wider spread of ages would be desirable.

Maximum rut depths are just under 0.5 inch. This narrow range is also less than ideal for statistical modeling.

For this modeling effort, the list of independent variables has been essentially the same as for the non-overlayed pavements, except that data for both overlay and original pavements have been included.

Table 1 contains essential information for Model I. There are 9 variables in this model.

It is not surprising that certain variables from the original pavement appear to influence rutting in the overlay. However, it is interesting that penetration at 40 °F and aggregate retained on the 80M screen do not enter the model for non-overlayed pavements(1). Also note that the sign of the parameter for pen 40 indicates that as pen increases rutting decreases. Considering pen 40 in isolation, that is not logical.

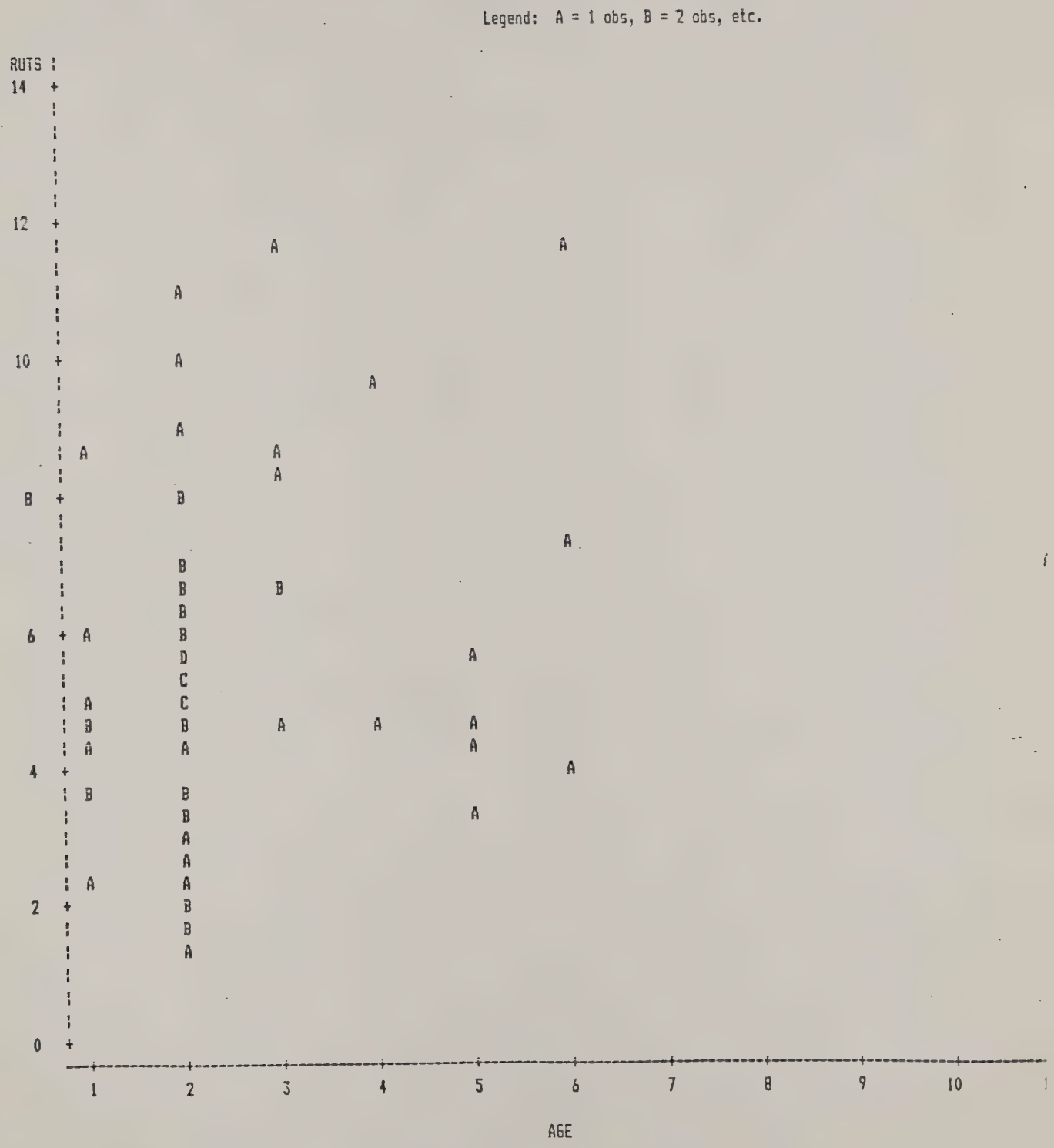


FIGURE 1. Plot of Rut Depths (mm) vs. Pavement Age for OGFC-containing Projects.

Table 1. Model I for rutting in overlays with OGFC

Variable	Parameter[8] Estimate	Standard[9] Error	Probability[10]
Intercept	-8.54	4.29	0.0528
Faces[1]	-0.08	0.02	0.0003
Agg. 40[2]	0.56	0.10	0.0001
Pen 40[3]	4.88×10^{-5}	9.3×10^{-6}	0.0001
K. vis*	-2.63×10^{-3}	9.1×10^{-4}	0.0059
A. vis	2.31×10^{-4}	1.3×10^{-4}	0.0855
Pen 40*[4]	-1.99×10^{-5}	8.7×10^{-6}	0.0272
Agg. 4[5]	0.43	8.9×10^{-2}	0.0001
% LMS[6]	-0.15	8.3×10^{-2}	0.0823
Agg. 80*[7]	-0.29	8.4×10^{-2}	0.0014
F value	13.564		
Adjusted R^2	0.6809		
No. of observations	53		

*Value of variable in original pavement

(1) Percent fractured faces in overlay
(2) Percent of aggregate retained on 40M after passing 10M
(3) Penetration of recovered asphalt at 40 °F x commercial traffic factor
(4) Penetration at 40 °F of asphalt recovered from original pavement x commercial traffic factor
(5) Percent of aggregate retained on 4M after passing 3/8" screen
(6) Percentage of LMS material in recovered overlay asphalt by HP-GPC
(7) Percent of aggregate in original pavement retained on the 80M after passing the 40M screen
(8) The amount by which the value of the variable is multiplied in the equation for the model
(9) The standard error for the parameter estimate
(10) An expression of the likelihood that the parameter is actually zero. A value of 0.0500 or less is most desirable (i.e., the probability is 5% or less that the parameter value is zero)

Nevertheless, none of these variables is isolated.

Just as in non-overlayed pavements, viscosities make very puzzling contributions to this model. In Model I, kinematic viscosity of the lower lift has a negative sign, i.e., as viscosity increases, rutting decreases as one might expect. Absolute viscosity of the upper lift also enters the model, but

with a positive sign. Measures of temperature susceptibility, including PVN, VTS, PI as well as the difference between the viscosity values (after converting to the same units) were put into the list of potential independent variables. However, none of these was found to be significant.

Model II. These seeming contradictions prompted the suggestion that a second model be constructed after removing outliers of both absolute viscosity and penetration at 40 °F of the lower lift from the list of potential variables. When this was done, there were several changes in the Model (See Model II, Table 2). For example, kinematic viscosity dropped from the Model. Also, Model II contains no reference to the percentage of fractured faces.

Table 2. Model II for overlay pavements with OGFC, absolute viscosity outliers deleted

Variable	Parameter Estimate	Std Error	Probability
Intercept	-15.15	3.97	0.0004
Agg 40(2)	0.50	0.10	0.0001
Minus 200	-0.54	0.16	0.0016
Pen 40(3)	5.5×100^{-5}	1.02×10^{-5}	0.0001
Agg 4(2)	0.42	0.08	0.0001
*Agg 80(2)	0.37	0.07	0.0001
%LMS(4)	4.4×10^{-5}	1.62^{-5}	0.0095

F value 17.784
Adjusted R^2 0.6595
Number of observations 53

*Values for original pavement

(2) Percent of aggregate retained on the screen having passed the next larger screen
(3) Penetration at 40 °F x commercial traffic factor
(4) Percent LMS in recovered asphalt x commercial traffic factor

In Model II, the percentage of minus 200 aggregate enters with a negative parameter. In non-overlayed pavements, the parameter for this variable was positive. This is not easily justified except to say that, for the overlay data set, lower percentages of minus 200 are associated with rutting.

The LMS content is modified by traffic levels in Model II and is more significant (probabilities: 0.0823 in Model I, 0.0095 in Model II).

Plots of residuals, that is the difference between predicted and measured rutting, for these models are in Figures 2 and 3. For Model I (Fig. 2), rut depths on all but 4 of the sites (8%) are predicted within ±2 mm; for model II, the data is similar. Model I predicts 33 sites (62%) within ±1mm; Model II predicts 65% within this range.

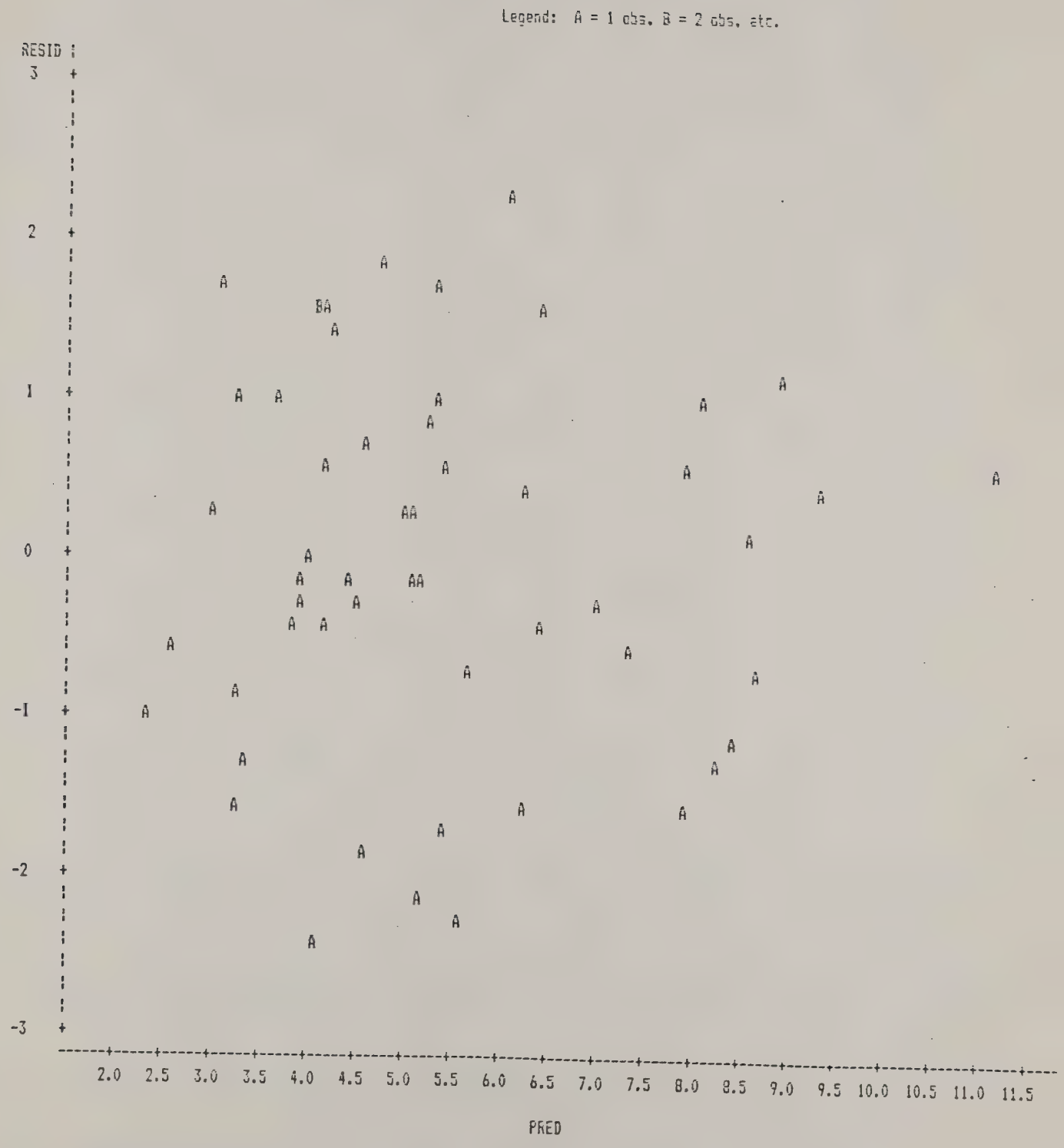


FIGURE 2. Plot of Residuals vs. Predicted Rut Depths (mm) for Model I.

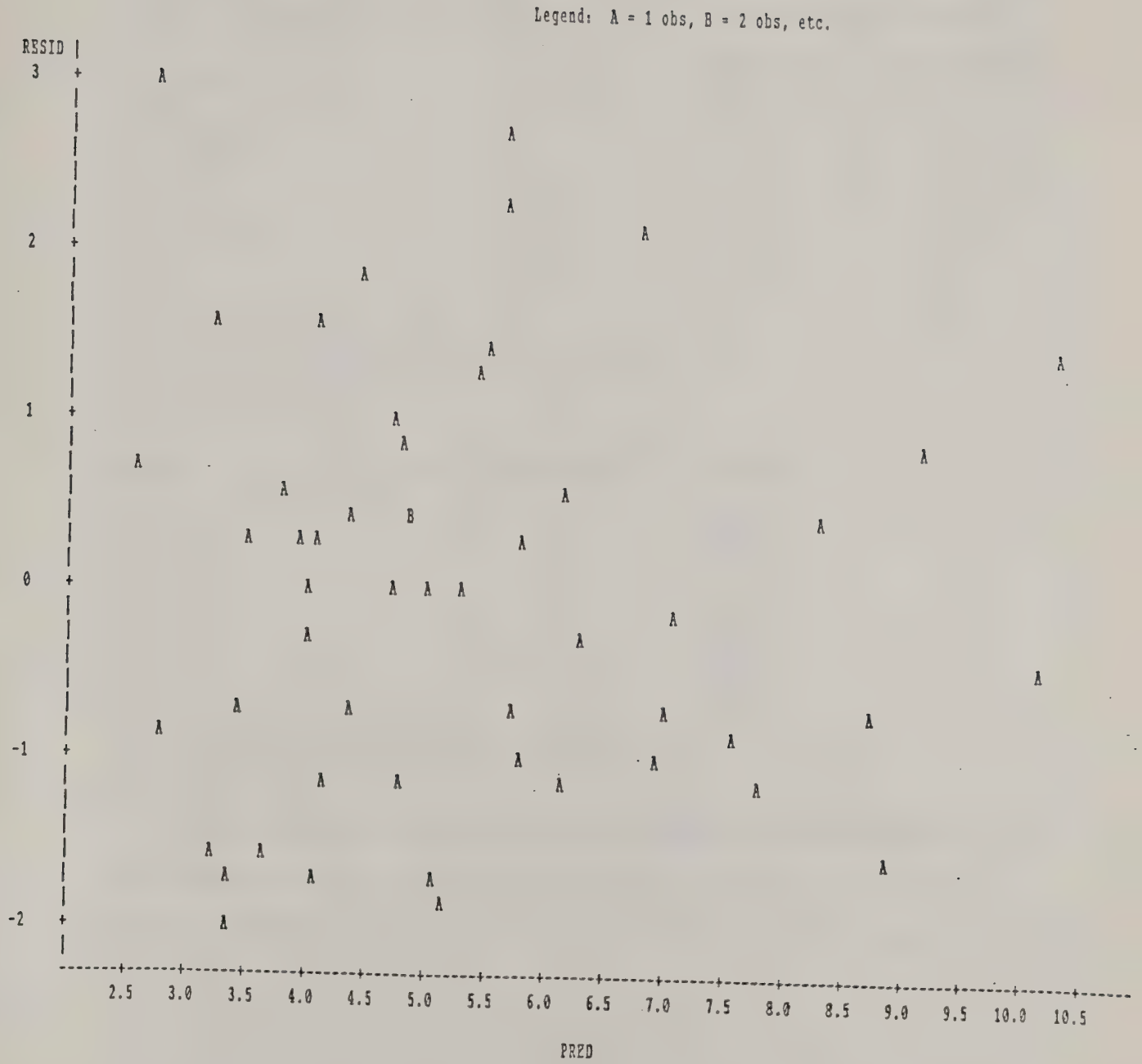


FIGURE 3. Plot of Residuals vs. Predicted Rut Depth (mm) for Model II.

Contributions of the variables in each of the models to rutting in overlays with OGFC are detailed in Tables 3 and 4.

Table 3. Contributions of Predictors to Predicted Rut Depth - Model I

	Site 23	Site 184
Intercept	-8.54	-8.54
Faces	-8.47	-6.50
Agg 40	9.45	10.34
Pen 40(1)	11.73	0.77
K. vis*	-2.13	-0.90
A. vis	0.52	1.38
Pen 40*(1)	-3.27	-0.54
Agg 4	13.55	9.76
% LMS	-3.50	-3.70
Agg 80*	1.81	2.04
Predicted rut depth, MM	11.2	4.1
Measured rut depth, MM	11.7	5.7

1) Modified by commercial traffic factor
*original pavement

Table 4. Contributions of Predictors to Predicted Rut Depth - Model II

	Site 23	Site 184
Intercept	-15.15	-15.15
Agg 40	8.75	9.25
Minus 200	-2.67	-3.59
Pen 40(1)	3.57	0.87
Agg 4	10.89	9.51
Agg 80*	2.62	2.62
% LMS(1)	-1.76	-0.79
Predicted rut depth, mm	10.3	2.7
Measured rut depth, mm	11.7	5.7

(1) Modified by commercial traffic factor
*original pavement

The potential range of contributions from the predictors for each model based on the values of the mean and the mean ± 1 standard deviation of the variable actually found in the data set are given in Tables 5 & 6.

Table 5. Calculated Range of Rutting Performance Based on Overlay plus OGFC Data Set - Model I

Predictor	Coeff.	Approx. Range	Theoretical Rut Depth, mm Min.(1)	Ave.(2)	Max(3)
Intercept	-8.54	--	-8.54	-8.54	-8.54
Faces	-0.08	(86 ± 9)	-7.60	-6.88	-6.16
Agg. 40	0.56	(18 ± 3)	+8.4	+10.08	+11.76
Pen 40(4)	4.88×10^{-5}	(29 ± 8)	+0.36	+2.73	+5.09
K vis*	-2.63×10^{-3}	(614±330)	-2.48	-1.61	-0.75
A vis	2.31×10^{-4}	(3980±2589)	+0.32	+0.92	+1.52
Pen 40*(4)	-1.99×10^{-5}	(26±11)	-2.06	-1.03	-0.00
Agg 4	0.43	(24±4)	+8.60	+10.32	+12.04
% LMS	-0.15	(22±3)	-3.75	-3.30	-2.85
Agg 80*	-0.29	(10±3)	-3.77	-2.9	-2.03
			-10.52	-0.21	10.08

(1) based on mean - 1 standard deviation
(2) based on mean
(3) based on mean + 1 standard deviation
(4) x commercial traffic factor
*original pavement

Table 6. Calculated Range of Rutting Performance Based on Overlay plus OGFC Data Set - Model II

Predictor	Coeff.	Approx. Range	Theoretical Rut Depth, mm Min.(1)	Ave.(2)	Max.(3)
Intercept	-15.15	-	-15.15	-15.15	-15.15
Agg 40	0.50	(19±4)	+ 7.50	+ 9.50	+11.50
Pen 40(4)	5.5×10^{-5}	(29±8)	+ 0.43	+ 3.11	+ 5.79
Minus 200	-0.54	(7±1)	- 4.32	- 3.78	- 3.24
Agg 4	0.42	(24±4)	+ 8.40	+10.08	+11.76
% LMS(4)	-4.4×10^{-5}	(22±3)	- 3.18	- 1.83	- 0.48
Agg 80*	0.37				

(1) based on mean - 1 standard deviation
(2) based on mean
(3) based on mean + 1 standard deviation
(4) modified by commercial traffic factor
*original pavement

The percentage of fractured aggregate appears to make a significant contribution to rut resistance in sites 23 and 184 using Model I (Table 3). However, the variable does not enter Model II. Moreover, data in Table 5 show a difference of only 1.5 mm of predicted rutting over the range mean ±1 standard deviation (77-95% of aggregate larger than 4M with at least one fractured face). In other words, the percentage of fractured aggregate is important and the highest possible percentage is desirable, but the variable is fairly well controlled in these pavement layers.

Other aggregate variables contribute to both models. Model I seems to indicate that the amounts of aggregate retained on the 4 and 40 M screens should be decreased and the amount retained on the 80 M increased. However, the ranges in the data set do not permit one to define the limits of these changes, nor do they indicate where the slack may safely be taken up. Similar comments could be made about aggregate variables in Model II. Four of the six variables in Model II do derive from the aggregate gradation, however, emphasizing the importance of this characteristic of the mix.

The penetrations at 40 °F of the asphalt recovered from both overlay and original pavement enter Model I. Both are modified by commercial traffic factor. Over the range of values in the data set, pen 40 (overlay) could contribute as much as 5 mm of rutting. Pen 40 in the original pavement has a negative

coefficient, but its contribution is very small. Only pen 40 of the overlay enters Model II.

The percentage of LMS does not make a large contribution in Model I ("saving" from 2.8 to 3.7 mm of rutting). However, the range of LMS contents is rather narrow. When modified by commercial traffic factor, as in Model II, the contribution of % LMS is somewhat greater, but still small.

Model for Overlays With and Without OGFC

In this modelling effort, the data for all overlays and their corresponding original pavements were used. The presence or absence of an open graded friction course was used as a potential variable.

Figure 4 contains a plot of rut depth versus age for this data set. Overlays with OGFC are designated 0, those without by +. This is a larger data set than was used for Models I and II. However, although the maximum age is 11 years, the mean age is 3.3 years and 18 pavements are just two years old. Maximum rut depth is 15.7 mm (about 0.6 inch). In terms of confidence in model building, this situation is marginally better than that for Models I and II.

Table 7 contains information about Model III, constructed for this data set.

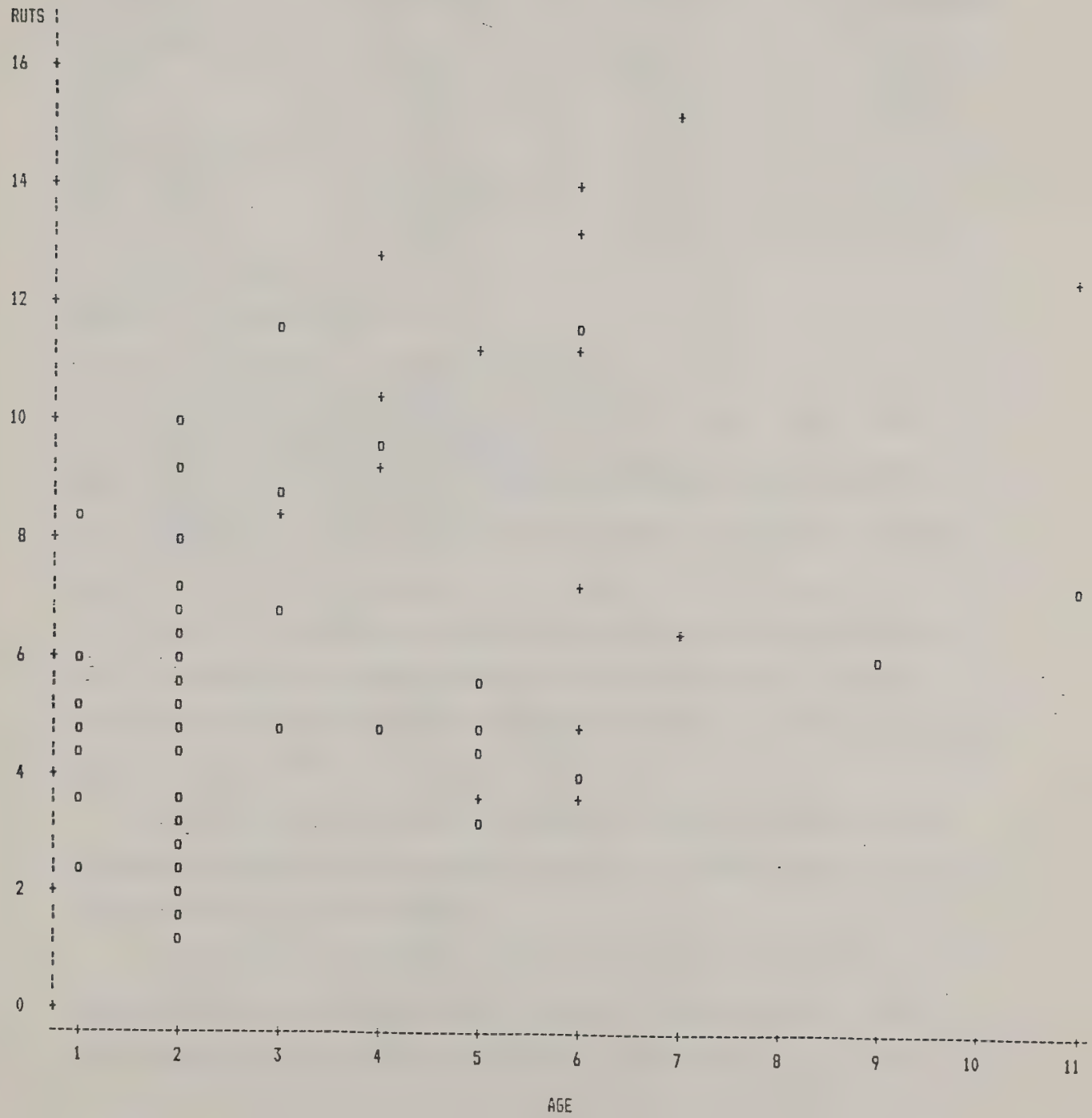


FIGURE 4. Plot of Rut Depth (mm) vs. Age of Pavement for OGFC-containing (+) and other overlays, (O).

Table 7. Model III for all overlay pavements

Variable	Parameter Estimate	Standard Error	Probability
Intercept	15.47	2.57	0.0001
Faces(1)	-0.09	0.02	0.0005
OGFC	-2.90	0.62	0.0001
Age*	0.10	0.04	0.0099
Pen. 77	-0.04	0.01	0.0010
Agg. 0.375(2)	-0.24	0.09	0.0065
Agg. 80(3)	0.39	0.10	0.0004
Pen. 40(4)	5.3×10^{-5}	1.1×10^{-5}	0.0001
Agg. 40*(5)	6.2×10^{-5}	1.8×10^{-5}	0.0009

F value - 19.82
Adjusted R^2 - 0.6765
Number of observations - 72

*value of variable in original pavement
(1) Percent fractured faces in overlay
(2) Aggregate retained on 3/8 inch (0.375 inch) screen after passing the 0.5 inch screen.
(3) Aggregate retained at 80M after passing the 40M screen.
(4) Penetration at 40°F of asphalt recovered from overlay x commercial traffic factor.
(5) Aggregate retained at 40M for original pavement x commercial traffic factor.

Model III predicts rutting reasonably well as shown by the plot of residuals versus predicted ruts in Figure 5. Rutting in 79 percent of the sites is predicted to within ±2 mm of measured rutting and in 92%, to within ±3 mm.

Of the eight variables in Model III, four are aggregate-related, emphasizing the importance of aggregate gradation and fracture seen in other models.

The mechanism by which age of the original pavement is associated with rutting in the overlay is not obvious. However, the probability is 0.0099 for this variable and it has been

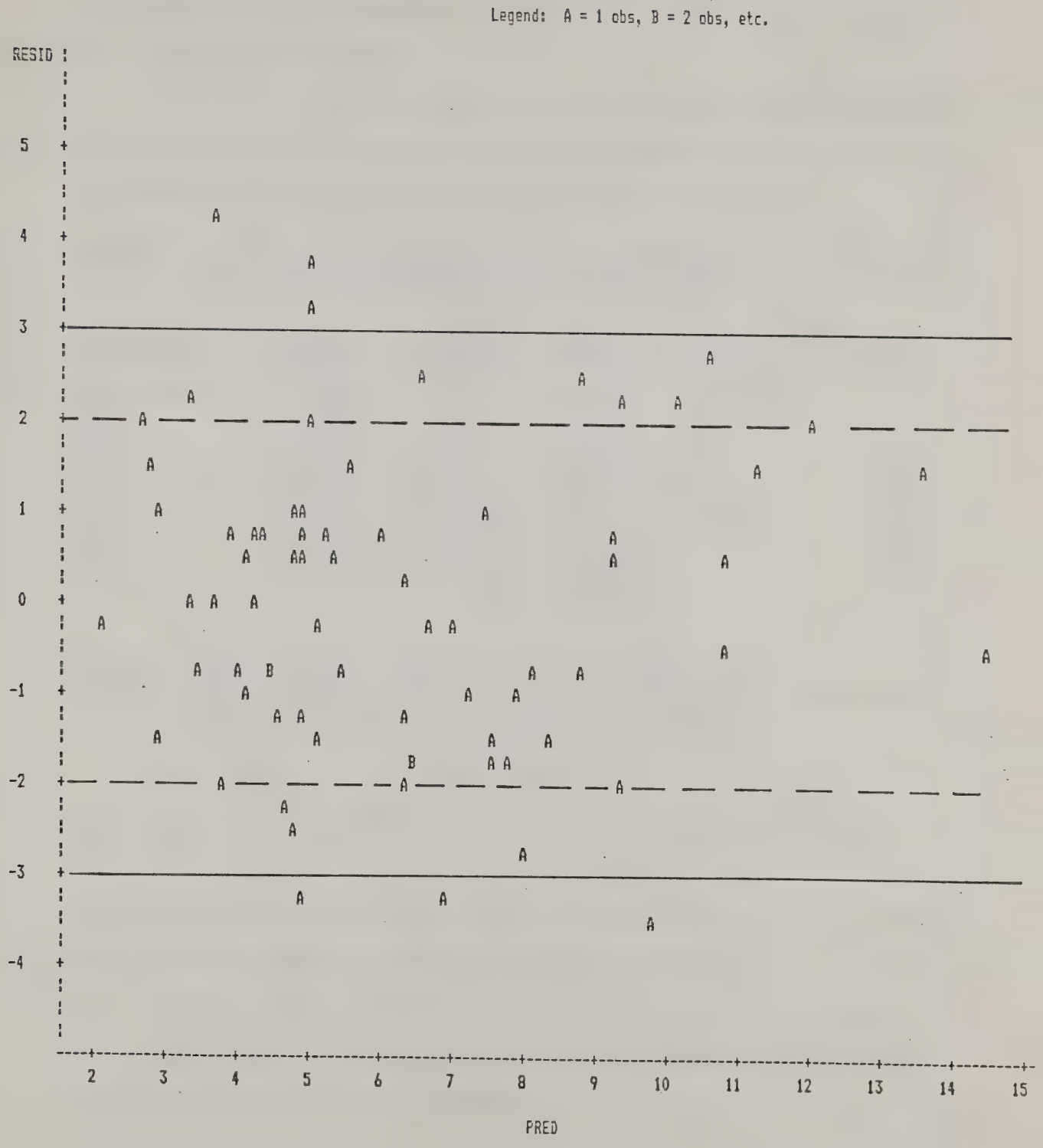


FIGURE 5. Plot of Residuals vs. Predicted Rut Depth (mm) for all overlays.

determined that this age is not a spurious entry resulting from its association with another variable(s). Nevertheless, it is not a controllable quantity.

Calculated potential contributions of each of the variables to rutting based on the mean value ±1 standard deviation for the variables found in the data set are given in Table 8.

Table 8. Calculated range of rutting performance based on data set for overlay pavements, Model III.

Predictor	Coeff.	Approx. Range	Theoretical Rut Depth, mm. Min.(1)	Ave.(2)	Max.(3)
Intercept	15.48	--	15.48	15.48	15.48
Faces	-0.09	85±10	-8.55	-7.65	-6.75
OGFC	-2.90	0 or 1	-2.90	--	0.00
Age*	0.1	--	1.69	1.69	1.69
Pen. 77	-0.04	67±28	-3.80	-2.68	-1.56
Agg. 0.375	-0.24	12.3±2.6	-3.58	-2.95	-2.33
Agg. 80	0.39	9.0±2.5	2.54	3.51	4.49
Pen. 40	5.3×10^{-5}	30.3±8.7	2.85	4.01	5.16
Agg. 40*	6.2×10^{-5}	18.7±4.1	2.86	2.86	2.86
			6.59	14.27	19.04

*for original pavement. Because these variables are uncontrollable at the time an overlay is placed, the mean value of the variable is used in all cases as an example.

The contribution of fractured faces in the aggregate is important, but the differences in that contribution over the range actually found in the data set is rather small. In fact, the same might be said for all of the predictor variables. The "theoretical" range of rutting based on this data set is 0.27 to 0.78 inches. This, no doubt, reflects the nature of the data set. The ranges of values of predictor variables actually found in these overlays are not very wide.

Conclusions

The statistical modeling of rutting in overlay pavements is hampered to some degree by the narrow range of ages and rut depths as well as of other variables in the subject pavements and by the lack of data on open graded friction courses associated with these overlays.

Nevertheless the models obtained emphasize the importance of aggregate gradation in the overlays. They also indicate a contribution from a lower temperature parameter, the penetration at 40 °F. Moreover, the models show that certain characteristics of the original pavement may influence rutting in the overlay. It is unfortunate that data on the rut depths in the original pavements at the time of overlay is not available.

Task 3. Statistical Analysis of Cracking on the Montana Interstate System

Introduction

Although presently overshadowed by rutting with its immediate safety aspects, cracking continues to be a problem in Montana. HP-GPC studies have indicated that molecular size profile can point toward a tendency to crack. However, even the best asphalts by this criterion sometimes crack. Unfortunately, other contributory factors are not well-defined.

When field performance data were collected for the rutting study [(1) and Task 1], crack counts were made at each sampling site. Therefore, data was available to carry out a statistical modelling study of the relationship of cracking to an extensive list of parameters. This study has been carried out with the help of statistician Tom Kalaris.

The Data

Details concerning the design of the study and the nature of the data are available in a previous report (1).

As with analysis of the rutting data, the cracking data is complicated by the presence of overlays. In an overlay it is usually not possible to tell whether cracks are reflected from the original pavement or inherent in the overlay itself. Furthermore, little if any cracking data is available for the original pavements. Therefore, it was decided to restrict the analysis to those pavements without overlays. Unless specifically noted, the remainder of this discussion will focus

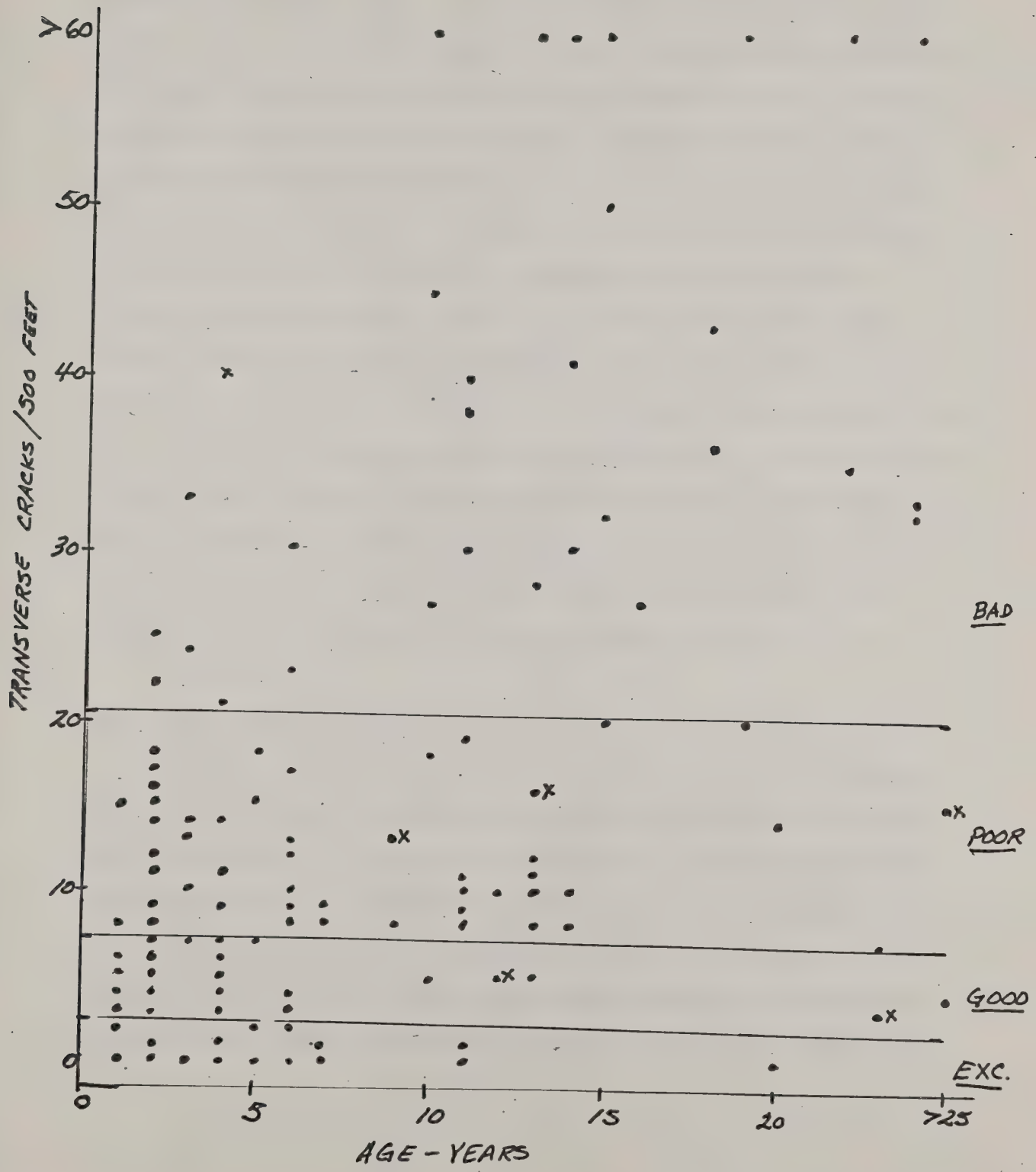
on those pavements which have not received dense- or open-graded overlays.

Before beginning that discussion, however, it is of interest to look at the condition of the Interstate System with and without overlays in 1986 with regard to cracking. Figure 3-1 plots the total number of transverse cracks counted in each 500-foot sampling site against the age of the uppermost lift for 137 projects the age of which was known. More than one site may be represented by a point, especially for pavements (mostly overlays) which were two years old. Twenty-three percent of the pavements were in bad condition with regard to cracking. An additional 40% were classified "poor," and 27% "good." Less than 10% were in excellent condition.

There is a general trend toward increased cracks with advancing age, but the scatter of data indicates the influence of other factors. There were a few pavements that remained in good condition after as many as 25 years. However, there were a dismaying number of projects that had deteriorated seriously after only a few years. Particularly disappointing was the performance of a group of overlays constructed in 1984. Of 39 original paving projects overlayed at that time, only six remained in excellent condition after two years; 22 were "good" whereas 18 had already reached the "poor" or "bad" categories.

It was visible in some cases that the cracks in these overlays had reflected from the original pavement. However, it was not possible to quantify the extent of reflection. To obtain

FIGURE 3-1. TOTAL TRANSVERSE CRACKS VS AGE FOR INTERSTATE PAVEMENTS



some basis in fact for a reflective cracking rate, cracks were mapped on a one-mile section of I-90 near Whitehall in June, 1988(MP. 244-245, E.B.). A total of 128 full-width transverse cracks plus some longitudinal and other short cracks were noted. The major transverse and longitudinal cracks had been filled in preparation for the construction of a 0.3' plant mix overlay immediately thereafter [IR 90-5(47)240]. In late March, 1989, the area was resurveyed. A total of 80 reflected full-width transverse cracks were found; no additional transverse or longitudinal cracks were noted. In other words, 65% of the full-width transverse cracks had reflected through in just one winter. While it is true that the winter '88-'89 was a particularly harsh one, it is not possible to ascertain its effect on the cracking rate. [Note: to plot points in Figure 3-1 for these before-and-after observations, the original pavement was 22 years old and had approximately 12 total transverse cracks/500 feet; the overlay at one year had 8 total cracks/500 feet.]

The Statistical Analysis

Simple correlations of the number of full-width transverse cracks with factors in the lengthy list of possible variables were obtained. No correlations were found between transverse cracking and the following individual variables: penetration grade of original asphalt, asphalt content of pavement, voids content, PVN or other temperature susceptibility measurements, penetrations, %LMS, commercial traffic factor, and Kinematic

viscosity, among others. Values of r^2 for other variables did indicate possible relationships: age ($r^2 = 0.0021$), absolute viscosity ($r^2 = 0.0005$ - this property was skewed by 3 very high values; when these unusual values were omitted, no relationship with cracking was indicated), viscosity temperature susceptibility modified by age ($r^2 = 0.0003$), %SMS modified by age ($r^2 = 0.0003$), PVN modified by age ($r^2 = 0.0001$). However, as will be seen when the model for cracking is discussed, these variables may not contribute to the overall picture.

The Model

The statistical modeling for cracking proved to be very difficult. Numerous efforts to achieve a stable model were made, but results which seemed reasonable on the surface were not viable on statistical grounds. On the other hand, the best model which was achieved, mathematically speaking, is not particularly satisfactory in terms of being helpful to MDOH in its efforts to minimize pavement cracking. Essential information for the model is contained in Table 3-1.

This model resulted from a square root transformation: the equation for the model is

$$\sqrt{\text{number of cracks}} = a_1 x_1 + a_2 x_2 + \ldots\ldots,$$

where a is the value of the parameter and x is the value of the corresponding variable. Using the data set on which the model was constructed, a plot of the predicted number of cracks against the difference between predicted and actual number can be made.

Table 3-1. Model for Cracking in Non-Overlayed Pavements

Variable	Parameter[1] Estimate	Standard[2] Error	Probability[3]
Intercept	1.50	2.29	0.5160
% Asphalt[4]	1.01	0.26	0.0002
Age	0.14	0.03	0.0001
Region 4[5]	1.92	0.41	0.0001
Agg.80[6]	-0.14	0.05	0.0141
Agg. 4[7]	-0.13	0.04	0.0036
Minus 200[8]	-0.26	0.11	0.0213
Fvalue	17.363		
Adjusted R^2	0.6091		
No. of observations	63		

(1) The amount by which the value of the variable is multiplied in the equation for the model.

(2) The standard error for the parameter estimate.

(3) An expression of the liklihood that the parameter is actually zero. A value of 0.0500 or less is most desirable (ie., the probability is 5% or less that the parameter value is zero).

(4) Percent of asphalt recovered from roadway cores.

(5) A climate region of the state having highest August temperatures, encompassing much of the eastern portion of Montana (see reference 1).

(6) Percent retained on the 80M screen having passed the 40M.

(7) Percentage retained on the 4M having passed the 10M screen.

(8) Percentage of aggregate which passed the 200M screen.

This plot (Figure 3-1) shows that the model predicts cracking moderately well with 94% of the sites being predicted within ±4 transverse cracks per 500 feet.

Analysis of Cracking Data (SQUARE ROOT TRANSFORM (zero values, no lrice, no ythick2)) - May 15, 1989

Plot of RRESID*PPRED. Legend: A = 1 obs, B = 2 obs, etc.

NOTE: 13 obs had missing values.

FIGURE 3-2. RESIDUALS VS. PREDICTED VALUES OF THE SQUARE ROOT OF TOTAL CRACKS

This plot (Figure 3-2) shows that the model predicts cracking moderately well with 94% of the sites being predicted within ±4 transverse cracks per 500 feet.

In Table 3-2 are tabulated the ranges of cracking that would be predicted by the model using the average of each predictor variable actually found in the data set as well as values of the average plus and minuses on standard deviation. For this exercise, age has been set at 10 years and climate region is not region 4.

Table 3-2

Param. x variable	Expected Cracks		
	Max	Ave	Min
Intercept	1.50	1.50	1.50
%Asphalt x 1.01	6.34	5.78	5.22
Age (10) x 0.14	1.40	1.40	1.40
Region 4	0.0	0.0	0.0
Agg 80 x -0.14	-0.97	-1.46	-1.95
Agg 4 x -0.13	-2.53	-3.03	-3.54
Minus 200 x -0.26	-1.32	-1.74	-2.16
cracks =	4.39	2.42	0.44
Expected cracks/500 ft.	20	6	0.2

There are some problems with the model. First, there is only one asphalt variable represented, that is asphalt content. Furthermore, the parameter is positive, indicating that cracking

increases as asphalt content increases. That might be rationalized in conjunction with another asphalt characteristic, but is more difficult to understand in isolation.

The climate zone variables used in modelling the rutting data also appear in the cracking model. Since those zones were based on highest temperatures, that is surprising. Lowest temperatures would seem to be more reasonably related to cracking. When one examines the average daily temperature data available for the state, one finds that, except for limited areas along the southernmost reaches of I-15, around Butte, and from Terry east on I-94, average temperatures for the three coldest months of the year are very similar. Data on the number of freeze-thaw cycles might be more valuable were it readily available.

Difficulty with the cracking model is disappointing but probably should not be surprising. Caution is always required when attempting statistical analyses on uncontrolled data sets. Crucial variables may be limited in range or may not have been measured, for example.

During the course of these studies, a considerable amount of time has been spent with the data. Although it is not possible to manipulate the large amount of data gathered in this study without the help of a computer, it is possible to find important information within the data set that is not specifically revealed by statistical analysis. The remainder of this section will address these efforts.

Not surprisingly, there is a relationship between the number of cracks and the age of a pavement. An ideal data set would have a full range of pavement ages. In this data set, however, most of the pavements are more than 10 years old and many are nearing the ends of their expected service lives. It is instructive, however, to inspect the data from the aspect of age.

There are just four pavements in this not-overlayed data set that are 5 years old or less (all are 4 years old) and three are performing well. Data from the Test Sections can be added, however, and that shows differences in performance (see Task 7, page 87), which, with the exception of Conoco, can be broadly related to HP-GPC chromatogram with some perturbations from additives. Note in Figure 3-3 that somewhat better performances (compared to Test Sections) are achieved in two pavements by Conoco at slightly higher LMS percentages. Also, that Cenex (without the SMS material seen in the Test Sections and, therefore, with more realistic LMS values) is performing nicely at four years.

In Figure 3-4 are nine pavement sections 6-10 years old. Only two of these do not have plant mix bases (PMB) which might be expected to slow cracking rates. This slowing of cracking rate may be happening with the Conoco section on PMB. That base was constructed with 200-300 grade asphalt. Conoco with fly ash (10 years) might be envisioned as foreshadowing the performance of the related Test Section. The seven year old Cenex section with base (no SMS shoulder) is not cracking. In the two Phillips

FIGURE 3-3. TOTAL CRACKS IN PAVEMENTS (NOT OVERLAYED) 1-5 YEARS

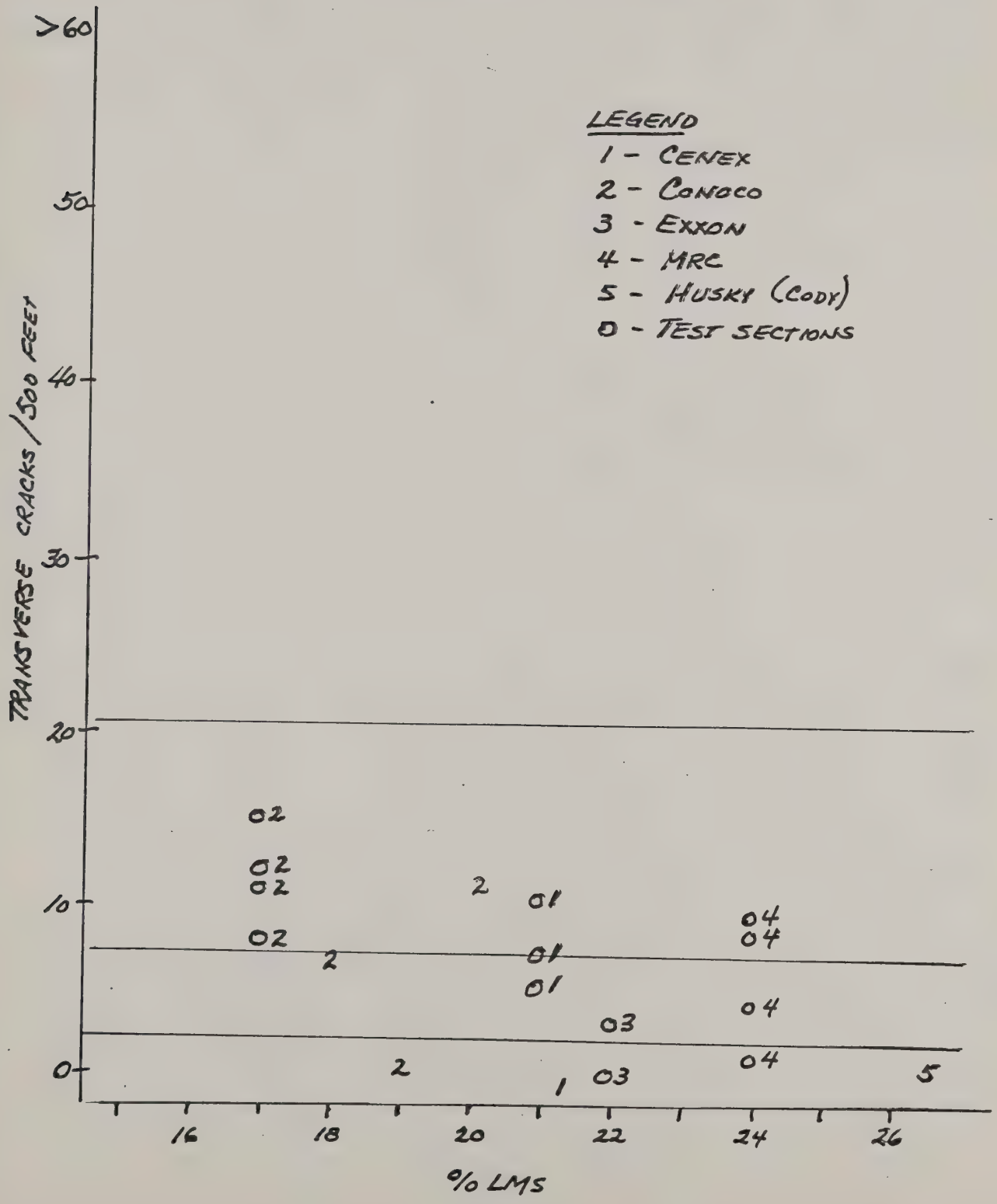
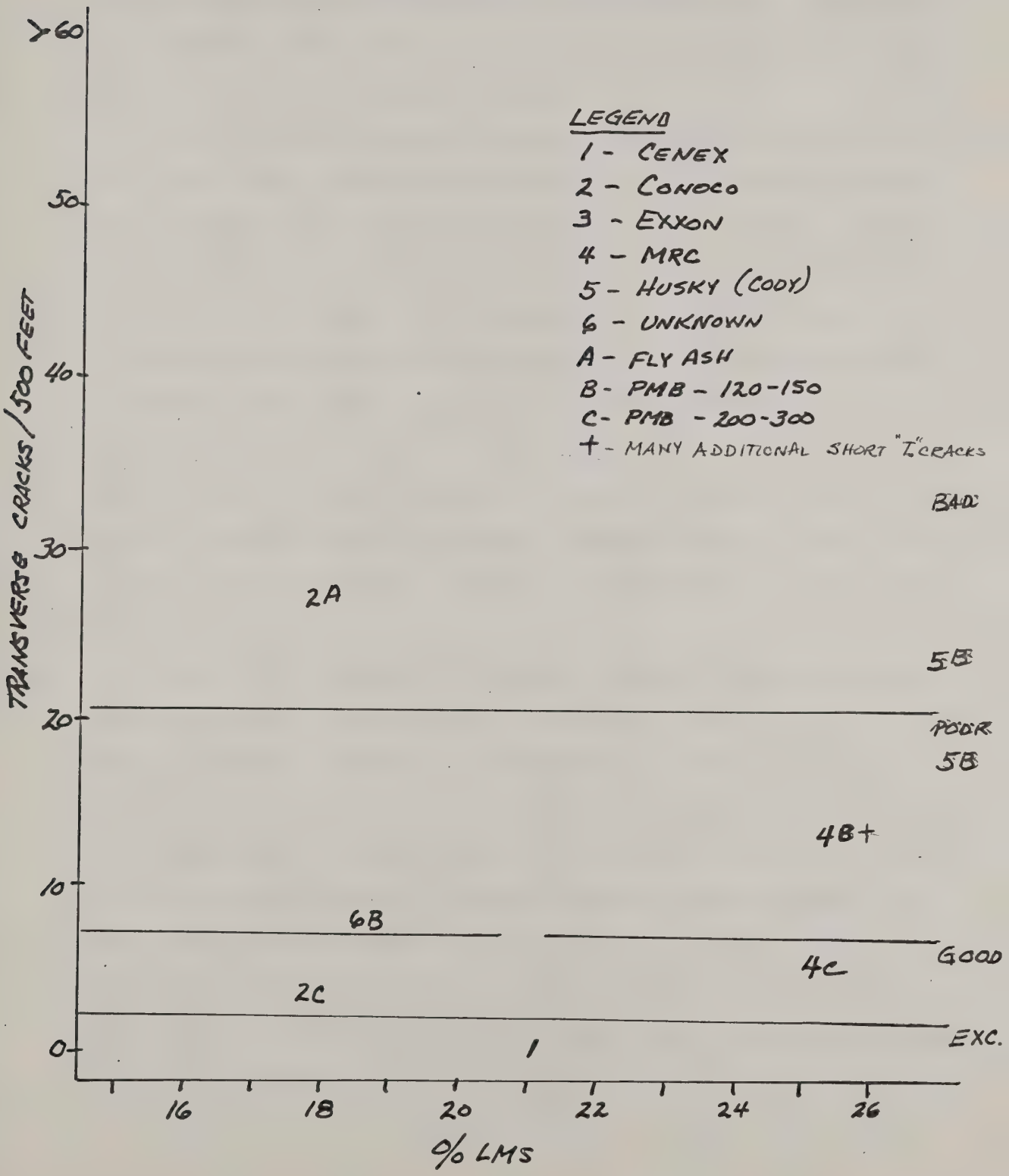


FIGURE 3-4. TOTAL CRACKS IN NON-OVERLAY, PAVEMENTS 6-10 YEARS



sections, 9 & 10 years old, both with slightly higher LMS contents than comparable Test Sections, that with a 200-300 grade PMB is performing much better than the section with lime and a 120-150 base. Two Husky sections, both six years old, at more than 27% LMS, are cracking severely.

Most of the pertinent pavements are between 11 and 15 years old. One might expect the broadest range of performance here and, indeed, Figure 3-5 shows that to be true. There are only four pavements with LMS percentages above 20; all of them are in poor condition. Only four pavements remain in the "good" to "excellent" categories; their LMS contents range approximately from 16 to 19%. Most of the rest of the pavements with less than 19% LMS are in the "poor" class, albeit in the better portion of that range. Many of the mixes in Figure 3-5 contain fly ash or lime, some have plant mix bases. However, none of these, or of other factors available, show a relationship to cracking in this data set.

All of the asphalts in pavements under 15 years old were 120-150 grade at construction (except two 200-300 pen asphalts used in PMB's). However, in pavements 16 years or more old (Figure 3-6), two of 14 used 85-100 pen asphalt, seven used 100-120, four used 150-200; only one pavement was constructed with 120-150 grade material. The best and the worst of these old sections were paved with 100-120 asphalt. That with about 20% LMS is in excellent condition. However, most of the asphalts with less than 20% LMS are in bad condition. Two other pavements

FIGURE 3-5. TOTAL CRACKS IN NON-OVERLAY PAVEMENTS 11-15 YEARS

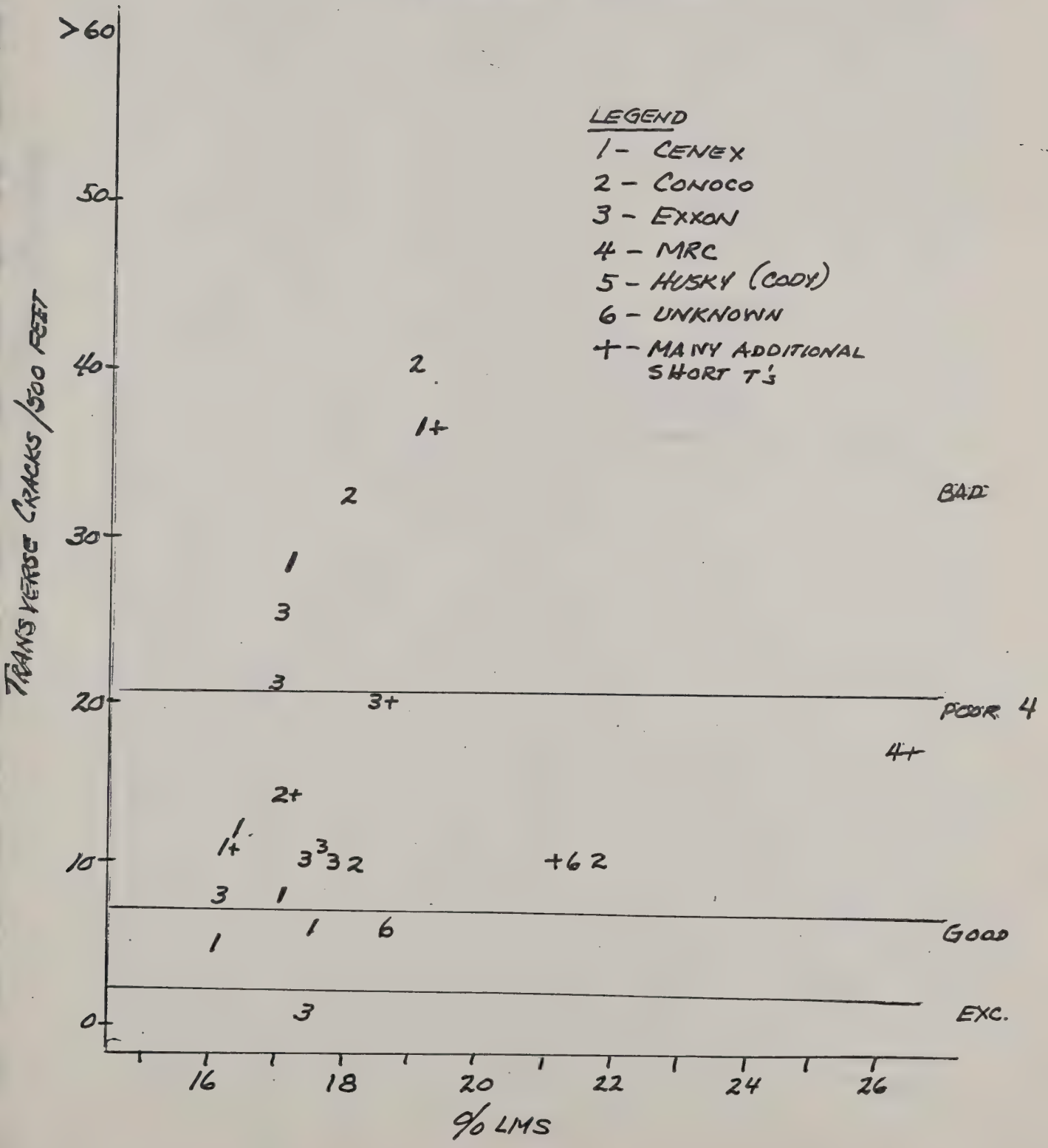
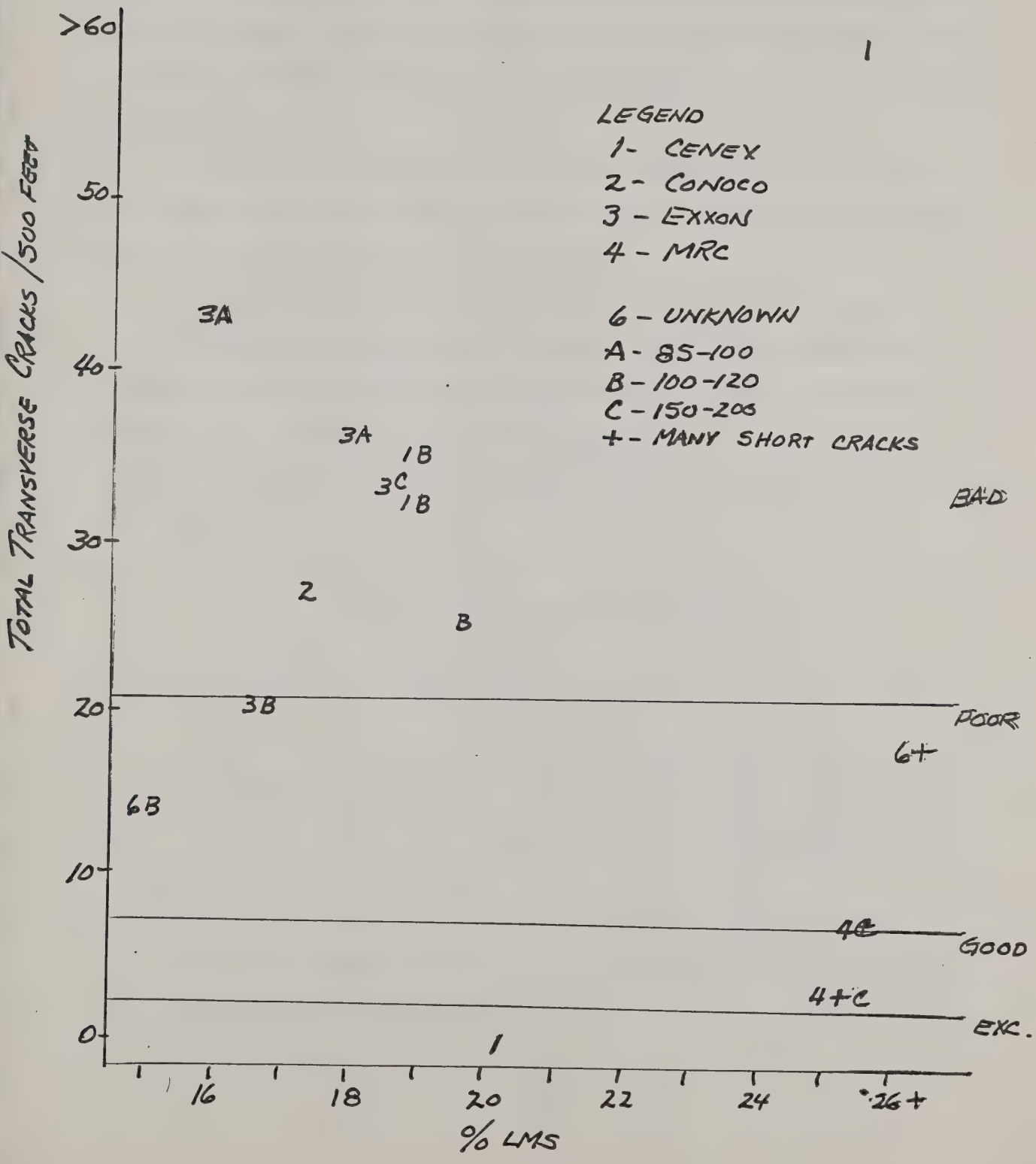


FIGURE 3-6. TOTAL CRACKS IN NON-OVERLAY PAVEMENTS ≥ 16 YEARS



in good condition after 23 years were constructed with 150-200 pen grade asphalt with about 25% LMS. It is interesting to note that the asphalts on which the Montana model was based were also 150-200 grade. It should also be noted that the rutting in these two very old sections was less than 0.5 inch in spite of the soft original asphalt.

Because of the differences in performance among products from different refineries, the data from non-overlayed pavements was also studied refinery by refinery.

Twelve sections containing Cenex asphalt range in age from 4 to 24 years, averaging about 15 years. Two are in excellent condition, one of these is 20 years old, the other only four years old. Two more are in good condition, the remainder are "poor" and "bad." There are no perceptible patterns in the group as a whole.

Table 3-3. Cenex Sections on I-15

Total Cracks	Additive	%AC	PMB	%LMS	%Voids	Vis	PVN	Pen Ratio
5	Lime	6.1		16.1	6.0	1258	-0.98	0.55
6	Fly	5.8		17.6	3.4	1982	-0.97	0.43
8	Flyash	6.2	X	17.6	4.9	1523	-1.03	0.48
11+	Lime	6.9	X	16.3	2.2	1240	-0.99	0.45
12	Lime	6.2	X	16.5	2.8	1036	-0.97	0.48
36+	Lime	5.4		19.3	5.3	2810	-0.81	0.71

+Numerous Short Transverse

There is, however, a set of six pavements, all constructed in 1973 between mile posts 39 and 94 on I-15 using 120-150 grade

Cenex asphalt. These sites constitute inadvertent "test sections" although the data set is too small for dependable statistical analysis (see Table 3-3). Two of the pavements are in good condition, three are "poor," one "bad." Without belaboring the details, it may be said that there are no obvious trends in the set. However, that project which has the most severe cracking also has the highest LMS content, the highest viscosity and the lowest asphalt content of the six pavements, as well as the lowest PVN and the highest pen ratio. If the historical data is accurate and this section was paved with the same material at roughly the same time, it is not possible to explain these discrepancies in the character of the aged asphalt with the known data. It might be speculated that the mix was overheated contributing to increased LMS content and excessive viscosity; perhaps the aggregate used was more reactive.

Eleven sections have been paved with Conoco products. The sections range in age from 4 to 16 years (10 years average) and the performance from excellent to bad. None of the sections more than 10 years old is in good condition. Five of the seven older sections are in the parts of the state with coldest winter temperatures but no other patterns are obvious.

Among the four younger sections (4, 5 and 6 years), that with the worst cracking performance has the highest LMS (still only about 20%, however) and the highest absolute viscosity of any of the Conoco pavements, regardless of age. Reasons for this are unknown but one might speculate, as for the Cenex situation

discussed earlier, about higher mix temperatures and/or more reactive aggregate.

Pavements with Exxon asphalts range in age from 10 to 24 years. Of the 14 projects, only two remain in good condition, seven are "poor." Fly ash was used in six projects, four of which are among the better performers of the group. (In the Test Sections, the Exxon trial with the most cracking is that with fly ash.) Limestone dust was used in four sections 18 and 19 years old, all are in bad condition.

Five adjacent sections, 10, 11 and 12 years old, form a possible "test section." The performance ranges from excellent to bad. The only apparent trends within the data are that PVN and penetration ratios differ significantly for the more seriously cracked sections (data for recovered asphalts). (Table 3-4). In fact, the cores from the best of those pavements were seriously stripped upon arrival in this laboratory. None of the others exhibited stripping.

Table 3-4. Five Sections with Exxon Asphalt

Total Cracks	Age	Additive	%AC	PMB	%LMS*	%Voids	Vis	PVN*	Pen* Ratio
1	11	Flyash	5.6		17.5	2.7	3396	-0.66	0.57
10	12	Flyash	5.2	X	17.8	1.4	8128	-0.80	0.50
11	11	--	4.5	X	17.7	6.9	9507	-0.65	0.56
18	10	--	5.2		17.9	1.4	6006	-0.97	0.48
25	12	--	5.1		17.2	5.1	2210	-1.08	0.49

*recovered AC

Pavement constructed with asphalts from the refinery at Great Falls (now Montana Refining Company, previously Simmons, nee Phillips) were among the more interesting of this study. The data in Table 3-5 shows three pavements, ages 9, 11 and 13, in poor condition. These are not surprising, based on the experience of the Test Sections. There is a 10 year old pavement in the "good" category, which would not be expected--it is on a plant mix base of 200-300 grade A.C. Even more surprising are the two good 23-year old sections. These were both constructed with 150-200 grade asphalt.

Table 3-5. Sections Containing MRC Asphalt

Total Cracks	Age	Additive	%AC	PMB	%LMS*	Grade	Vis	PVN*	Pen* Ratio
3+	23	?	5.5		24.8	150-200	2766	-0.81	0.53
5	10		5.3	X(1)	25.2	120-150	1245	-0.81	0.46
7	23	?	5.5		25.3	150-200	7808	-0.50	0.71
13+	9		5.2	X	25.4	120-150	5468	-0.64	0.40
16+	14		6.6	X	26.3	120-150	1536	-0.47	0.32
19	11	Flyash	5.7		28.5	120-150	6158	-0.82	0.59

+ many additional short transverse cracks

(1) PMB constructed with 200-300 grade AC

One might be tempted to say that pavement should be constructed with 150-200 grade material, or with 100-120 using mineral filler to avoid cracking. Obviously, there are contradictions to such assumptions. And in the end, the data

from the Interstate survey leaves us unable to draw firm conclusions about the causes of transverse cracking at least in part because we are using uncontrolled data. We do have, fortunately, the Test Sections which continue to show obvious differences in performance in a reasonably well-controlled experiment.

Task 4. Implementation of HP-GPC Analysis for 1988 Paving Season

This task was undertaken to begin to implement HP-GPC analysis on a semi-regular basis by monitoring eight construction projects. So that performance can be more effectively monitored in the future, the construction locations were visited before construction began, and measurements of both cracking and rutting as well as general notes about the condition of pavements to be overlayed were gathered. This information is collected in Appendix A.

Two sets of samples were obtained for each project. From the design phase, samples of the asphalt used and of the design Marshall mix were obtained. The mix was extracted. HP-GPC data for these will be labelled "AC design" and "Ext. Design," respectively.

Three sample types were collected during the construction phase: asphalt cement tested by MDOH for specification compliance ("Const. AC"), corresponding Thin Film Oven Test residues ("TFOT") and spent Marshall pucks from the Testing Trailer at the project. The latter were extracted for HP-GPC analysis ("Const. ext"). From this data, graphic comparisons between the asphalt cement used for the design and that used in the construction can be made. Also, the HP-GPC characteristics of the TFOT residues and the asphalts extracted from design and construction mixes can be compared. Even more, a measure of the variability of the asphalt before and after mixing can be achieved.

Figures 4-1 through 4-8 contain this data. The horizontal line represents the percent LMS of the sample (in the case of the design materials) or the average percent LMS (in the case of multiple samples). The open bar represents the range of values with the extreme values annotated for ease of reference.

For the project Circle-North [FBRF-HES 25-1(9)0], it can be seen that the construction asphalt cement is very similar to the design AC and that the asphalt used for construction was quite consistent with a total range of about 1% LMS. Also, the asphalt from the design mix and the pavement mix are much the same. More importantly, the range of LMS percentages is 1.2%. Although the average of the TFOT residues is very similar to the average of the construction extract, the range is very broad. In view of the apparent consistency of the other samples, one might assume that the results reflect some inconsistency in the TFOT itself. This project used Exxon/85-100 asphalt.

The circumstances for Galata-East and West [RTF 1-4(11)292] suggest that the asphalt used for construction contained less LMS than that used for design and that it was somewhat less consistant (range about 2%) than that used in the Circle-North project. The TFOT and construction extract average %LMS are significantly different from that of the design extract. Here, the range of LMS in the TFOT residues is quite narrow but the range in the construction extracts is very broad--nearly 11%. Although most of the values are about 22.5 to 23.0%, there are others near 26, 30 and 33%. Since the character

of the asphalt cement was reasonably consistent, it might be speculated that variations in the mixing temperature, in the reactivity of the aggregate, perhaps in overlong storage of the hot mix, could account for the variations observed in the final product. Construction used MRC/85-100 asphalt.

On the Kevin-North project [IR 15-8(44)380], variability in the construction asphalt cement of almost 3% is reflected to some degree in the TFOT residues but not, apparently, in the construction extract. However, most of the construction asphalts cluster tightly between 32.6 and 33.4% LMS with only one sample above 33.8%. This asphalt is Husky (Canada)/85-100.

Consistency of HP-GPC results were noted on both Plains-Paradise [F-BRF 6-1(13)76], and Kila-East and West [F-BRF-HES 1-2(37)99] projects, although the TFOT and design extracts are not particularly good predictors of the final product. The Plains project used Exxon/85-100, but the source for Kila is unknown.

Like Kevin, the Melrose-North [IR 15-2(56)93] project shows significant variability in the construction AC and TFOT residues and this is reflected in the construction extract. Melrose was constructed with Exxon/85-100.

The variability in the construction asphalts in both the Norris Hill [F-BRF 13-1(6)56], and Wolf Point [F1 10(18)593] projects is disturbingly large. However, although the variability is reflected in the TFOT data for Norris, it does not apparently affect the finished product in either case. In fact for Norris, the LMS values for the construction asphalt range

from 14.1 to 16.3% with only one sample at 19.6% and one at 23.3%. A similar discrepancy exists for Wolf Point. Norris was paved using Conoco/85-100.

In five of these eight projects, the construction asphalt cements show a range between 1.1 and 2.0% LMS. In the remainder, the ranges are 3.1, 9.2 and 9.3%. However, in the final extracted products the LMS range narrows to between 0.9 and 1.3% in six projects, to 2.2% in one project and to 10.8% in one pavement. Considering that the HP-GPC technique is reproducible to within ±0.2% LMS, most of these projects can be considered to be very consistent in terms of molecular size distribution.

Circle

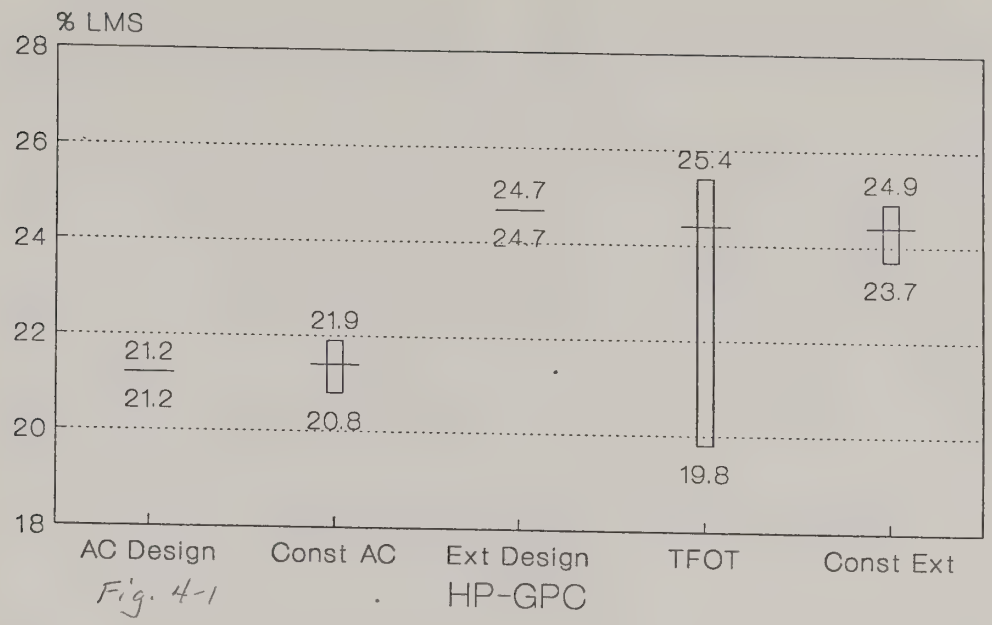


Fig. 4-1

Galata

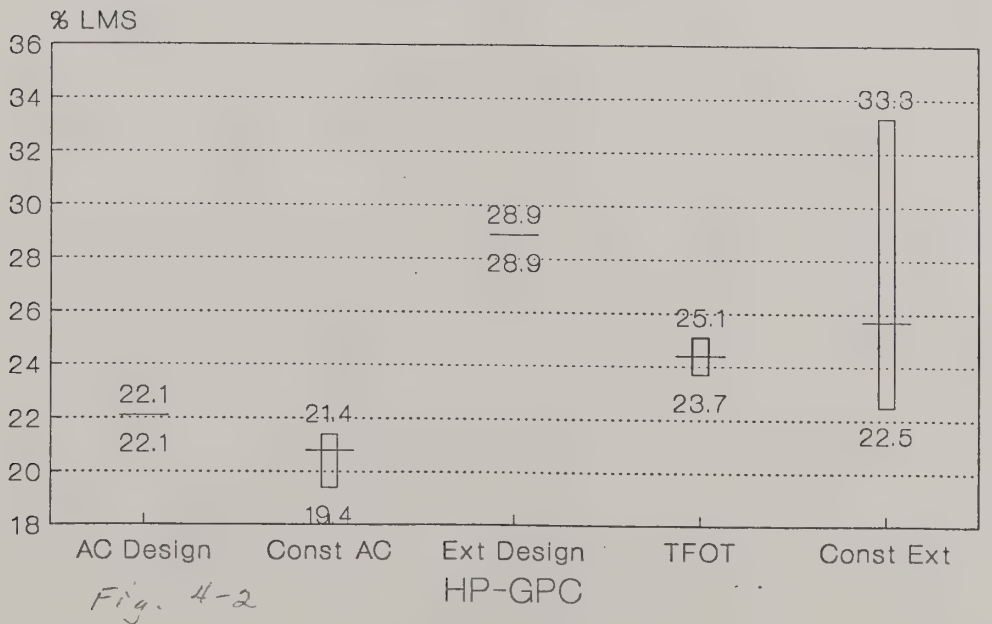


Fig. 4-2

Kevin

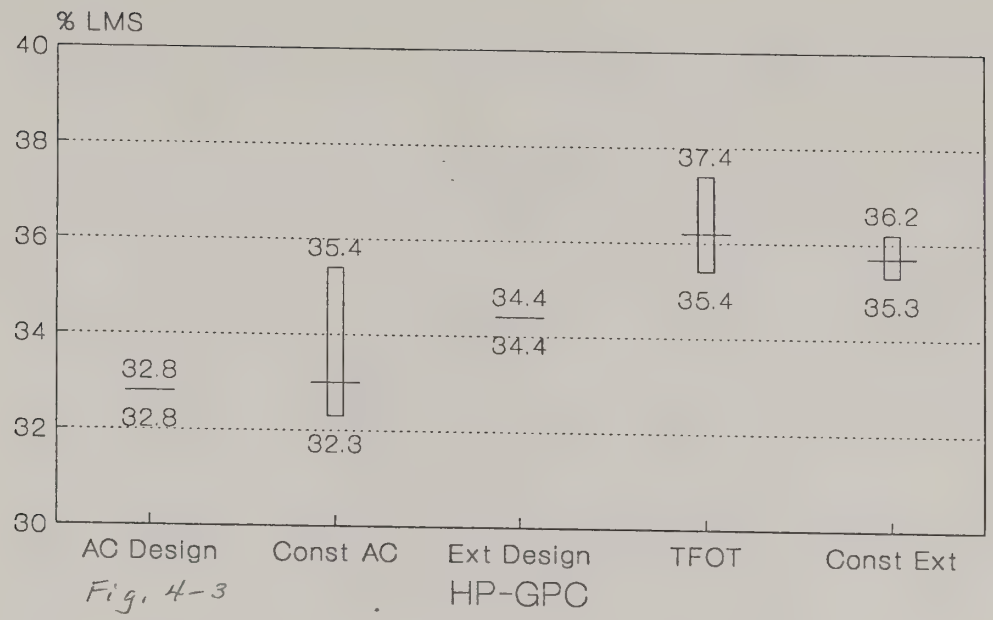


Fig. 4-3

HP-GPC

Plains-Paradise

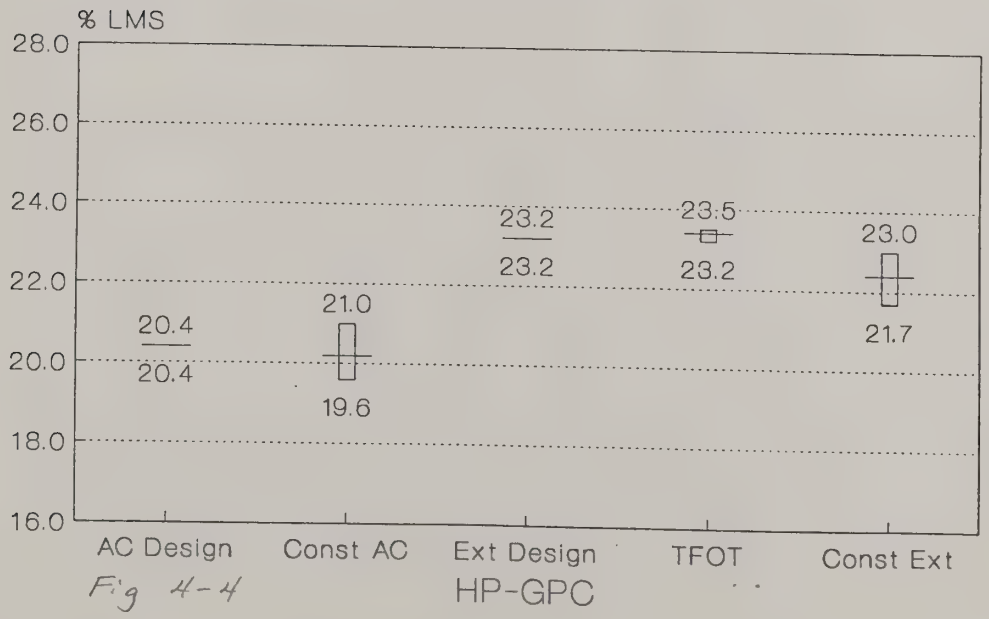


Fig 4-4

HP-GPC

Kila

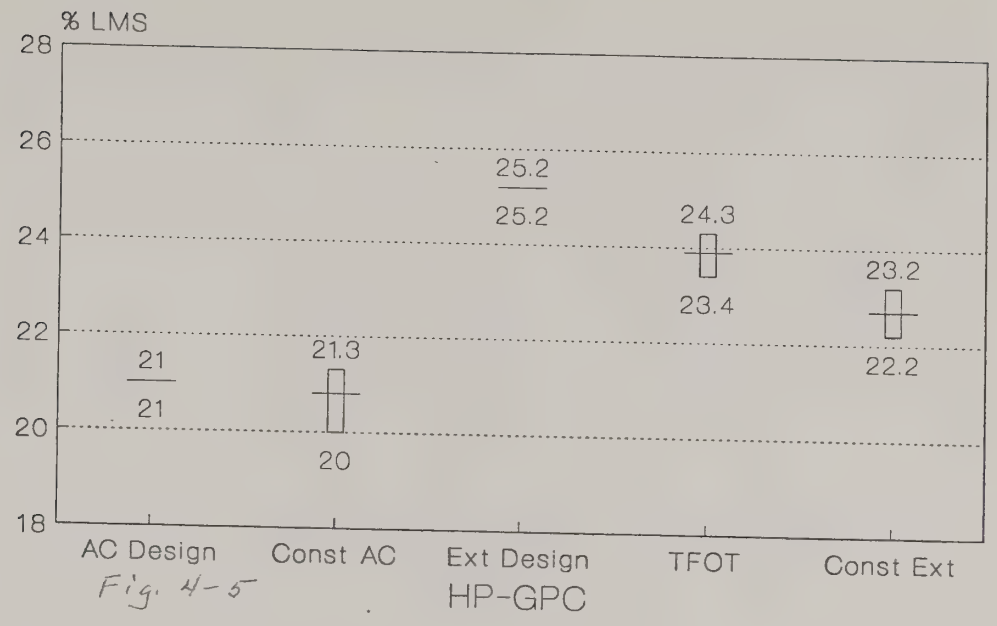


Fig. 4-5

Melrose

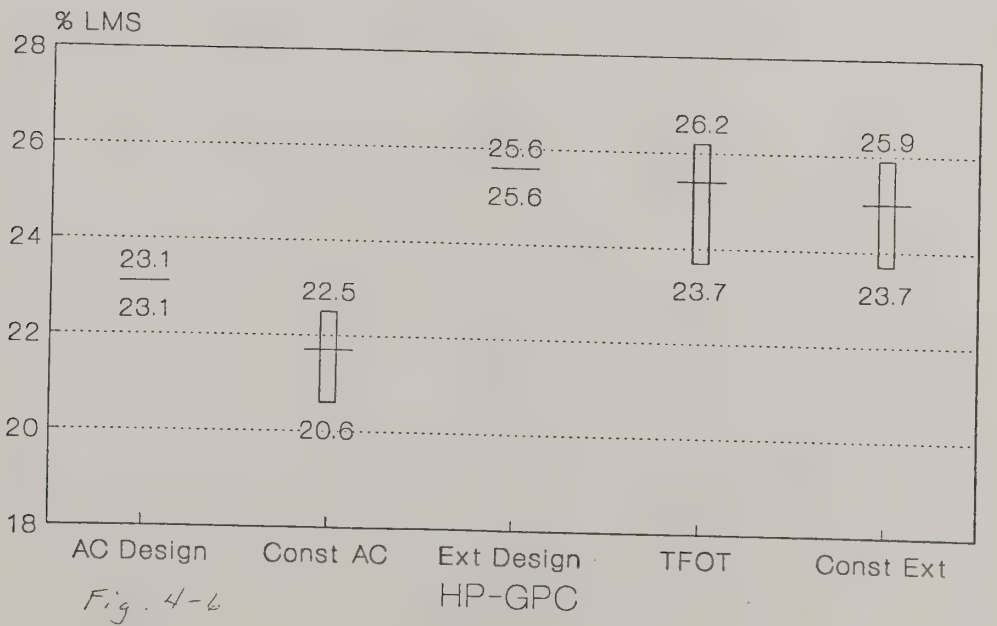


Fig. 4-6

Norris

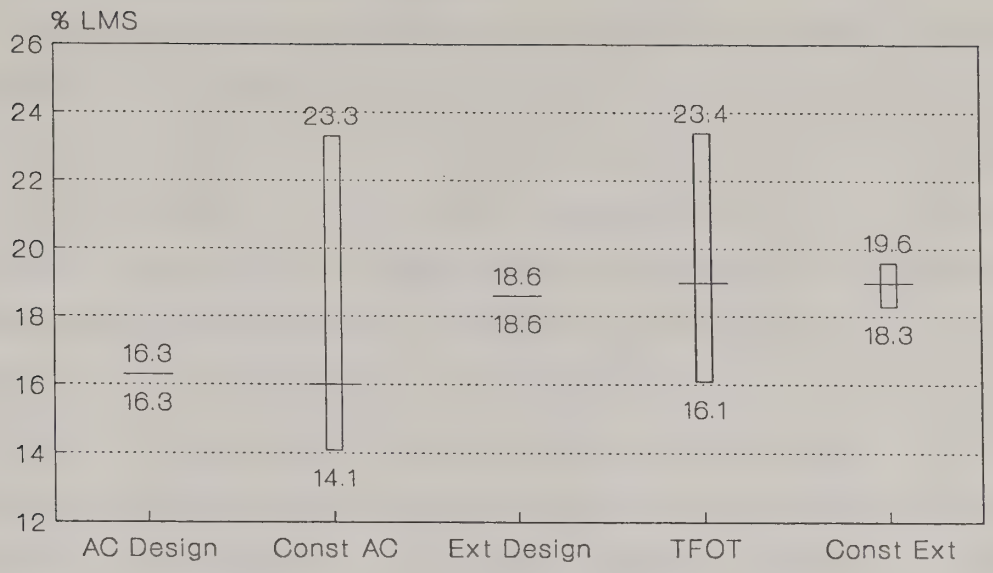


Fig. 4-7

HP-GPC

Wolf Point

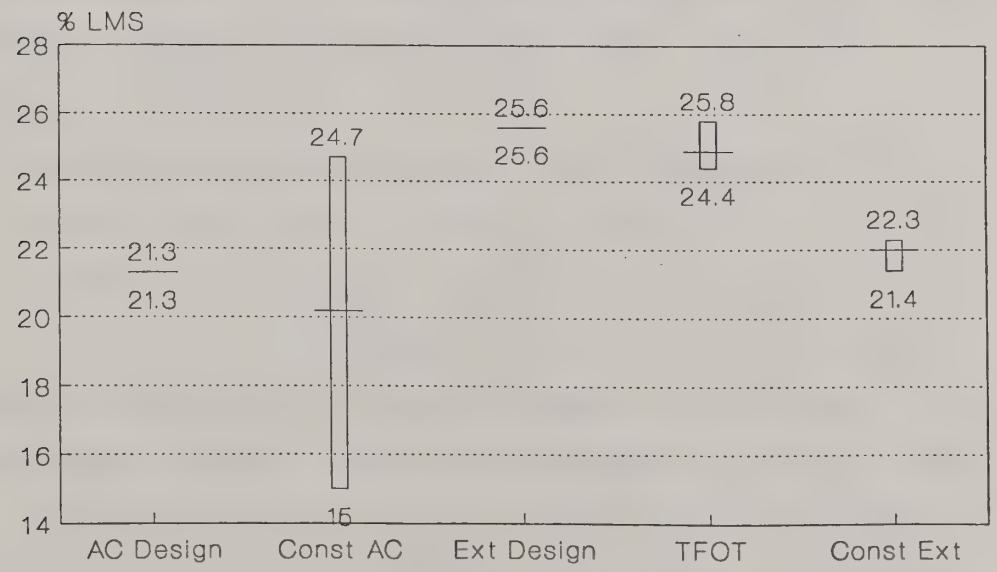


Fig. 4-8

HP-GPC

Task 5. Construction Variables

Work on the Test Sections and the Rutting Study called to attention the variability that can and does occur in the course of pavement construction. Of immediate concern is the validity of relationships between certain parameters, eg., percent voids or asphalt content, and performance. Variability introduced by construction and the testing procedures themselves can throw doubt upon any correlations, particularly in small data sets. Therefore, it is important that MDOH be aware of the variability, both construction and test method derived (it may, in fact, not be possible to separate the two sources) so that construction quality and correlations with performance can be accurately assessed.

Five construction projects were selected for this Task, one from each district. For one of these projects, the construction schedule thwarted inclusion in the study. Four construction projects were monitored:

Bloomfield - North RS 254-1(6)26 - overlay

Custer - East IR 94-1(49)47 - overlay

Helena - West RTF-BRF 8-2(15)34 - reconstruction

Potomac - West F-BHF-BRF 24-1(25)9 - reconstruction

These construction sites were surveyed before paving; the performance data for underlying pavements is noted in Appendix A.

A variety of sample and data types were collected; it is necessary to define these before proceeding with the discussion.

From the mix design phase, a sample of the asphalt cement used by MDOH as well as a sample of the design mix were submitted.

During construction of the projects, MDOH obtained samples by lot of the asphalt cement from the storage tanks for specification testing. These samples as well as corresponding thin film oven test (TFOT) residues were submitted. Also during construction, MDOH collected samples for Marshall testing; the broken pucks were sent here.

These asphalt and Marshall samples are routine. However, two other sample types were collected from these four projects in an effort to quantify variability in the constructed pavement. These samples were collected on two to three successive days of construction. The first type were grab samples of mix from three successive truckloads. Six such sets were collected at intervals during the sampling period for a total of 18 grab samples per project. The second type were collected from the newly placed mat and are called site samples. On six occasions immediately following the collection of grab samples, samples were taken from the mat and immediately adjacent sites were marked on the new pavement in a pattern illustrated in Figure 5-1. Cores were eventually cut at each of those sites.

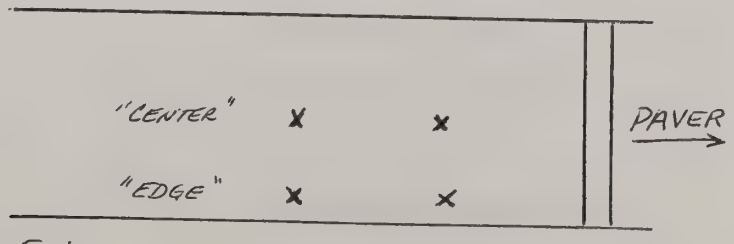


FIGURE 5-1.

A list of sample types and parameters, along with pertinent abbreviations follows.

Design:

- Design asphalt cement (Design AC)
  - Penetration
  - HP-GPC
- Marshall design puck (Design Marsh)
  - Marshall stability & flow
  - HP-GPC (Ext. design)
  - % Asphalt cement
  - % Voids

Construction:

- Construction asphalt cement (Const AC)
  - Penetration
  - HP-GPC
- Thin film oven test residues (TFOT)
  - Penetration
  - HP-GPC
- Marshall construction pucks (const. Marsh)
  - Bulk specific gravity
  - Rice specific gravity
  - % Voids
  - % Asphalt cement
  - Marshall stability & flow
  - HP-GPC
  - Aggregate gradations

Grab Samples (1-18)

% Asphalt cement

HP-GPC

Penetration @ 40 & 77°F

Viscosity: Kinematic & Absolute

Aggregate gradations

Site Samples (A-X) (Const. site)

Bulk specific gravity

Rice specific gravity

% Voids

Marshall stability & flow

% Asphalt cement

Nuclear density

All HP-GPC analyses were performed by MSU laboratories. Design sample analyses were performed by MDOH in Helena. Those samples identified as Construction samples, essentially four types, were analyzed as follows: Construction asphalt and Marshall construction testing parameters performed by MDOH; Grab and Site sample parameters performed by MSU except nuclear density which was performed in the field by MDOH personnel.

Discussion of the variability found in the pavement construction will be approached by reviewing some simple statistics for the construction type samples and then comparing these with related design type samples, the intent being the identification and quantification of variations, if any, within and among related sample types.

Bloomfield-North

The Bloomfield-North project [RS 254-1(6)26], was constructed with Conoco/120-150 asphalt cement over the period beginning 3 October through 14 October 1988. Field sampling during this construction period was performed on the 6, 7, 13, and 14th of October. Discussion of analytical parameters will begin with the HP-GPC data, specifically the LMS component of the design and construction samples.

Figure 5-1 is a graphical representation of LMS values obtained for each of the sample types; the horizontal line represents the average of the data set and the open vertical bar the maximum and minimum values, indicating range. Each is annotated for ease of review. Note that both the AC Design and Extracted Design percentage values are for single sample analysis. Interpretation of these graphs is fairly simple. First, it is apparent that the Construction AC samples analyzed are representative of the Design AC and have a small range of LMS values. (A 0.9% range is relatively small with respect to the ±0.2% analytical error.) Second, when comparing the remaining four sample types it is seen that great differences exist in the average LMS percentages and their ranges. Theoretically all should be similar. The TFOT data, which simulates the hardening effects of aggregate-asphalt mix preparation, has an average of 20.3% LMS, nearly 2% greater than the Extracted Design and 3% greater than the Construction Extract percentage of 17.5. Finally, the Grab sample data, reflecting mat construction

characteristics, has an average similar to that found in the Design and Construction Extract samples. The broad range found warrants a comment: the maximum of 22.4% LMS shown skews the graphical representation considerably since all other data points are within a 17.7 to 18.9% range. Although this maximum is extreme it should not be discounted as it may indicate a difference in mix processing.

Marshall stability and flow are graphically represented in Figures 5-2 and 5-3. Comparison of the sample types, Construction Marshall and Construction Site, demonstrate mechanical strength differences found for samples prepared under controlled laboratory conditions with those found in the actual pavement. The difference between averages is considerable and distributions are broad. The Design Marshall stability is included for reference.

One of the more critical parameters in pavement construction is the percent of asphalt found in the mix. Figure 5-4 compares four sample types; the design asphalt content, the Construction Marshall specimens prepared and analyzed in the field laboratory, and site and grab samples extracted in MSU laboratories. While it would appear that there is little variability in asphalt content as shown in the Construction Marshall samples, field samples indicate otherwise.

It may not be surprising to find that asphalt content in the mix as constructed differs from the design target. However, it is not so obvious why measurements of construction samples should

differ. At least part of the explanation may lie in the techniques used to measure the parameter. Asphalt content in the Construction Marshall samples is measured at the field testing laboratory using a calibrated nuclear instrument. The Construction Grab and Site samples were extracted using trahydrofuran (THF) as solvent. (Controlled experiments have shown that THF removes 100% of the asphalt added to an aggregate sample.)

A possible source of error with the nuclear instrumentation is calibration; with extraction error sources include weighing and incomplete removal of asphalt. One might feel a little more confident if the averages of asphalt content by the two methods were more nearly alike. In the Bloomfield samples, these averages differ by about 0.7%.

Bulk and Rice specific gravities and resulting percent voids are shown in the next three graphs. Rice specific gravities are comparable for the two sample types, bulk specific gravities have a larger range for the site samples and the voids contents reflect this.

Viscosity results are shown in Figure 5-8. Although there are no pre-mix data available for comparison, the data are instructive nonetheless. As seen here the extracted asphalt recovered from grab samples has a moderate range for absolute viscosity. The maximum value was obtained for the sample which contained maximum LMS. Kinematic viscosity has a somewhat smaller range.

Penetration data are available for both pre-mix and mix samples. Figure 5-9 graphs penetration results for three sample types (the grab samples were analyzed at both 77 and 40 degrees F.) The average for the AC Design was 131, and 109 for the grab samples, at 77 degrees. The broad range of penetrations for the grab sample data set, like that of the viscosity, is larger than anticipated and attributable to a variety of sources. For example, research performed by this group has found significant hardening in terms of penetration, on the order of 10 percent for an 85/100 asphalt, when trichloroethylene or tetrahydrofuran were used solely as a solvent in contact with the asphalt for the normal asphalt-solvent contact time usually observed when extracting asphalt from an aggregate. Combining this with the environment of mix plant as well as asphalt-aggregate interactions it is probably not surprising that a range of values such as found here result.

The figure for aggregate gradations plots the average, maximum and minimum for the samples in the usual line and open bar mode. The MDOH anti-rutting specification range is indicated by the area enclosed within the curves. From this plot, percent passing values for each aggregate fraction are visually examined to determine specification compliance. Here the 200-M and 10-M had minimum data just outside the minimum specification.

Bloomfield

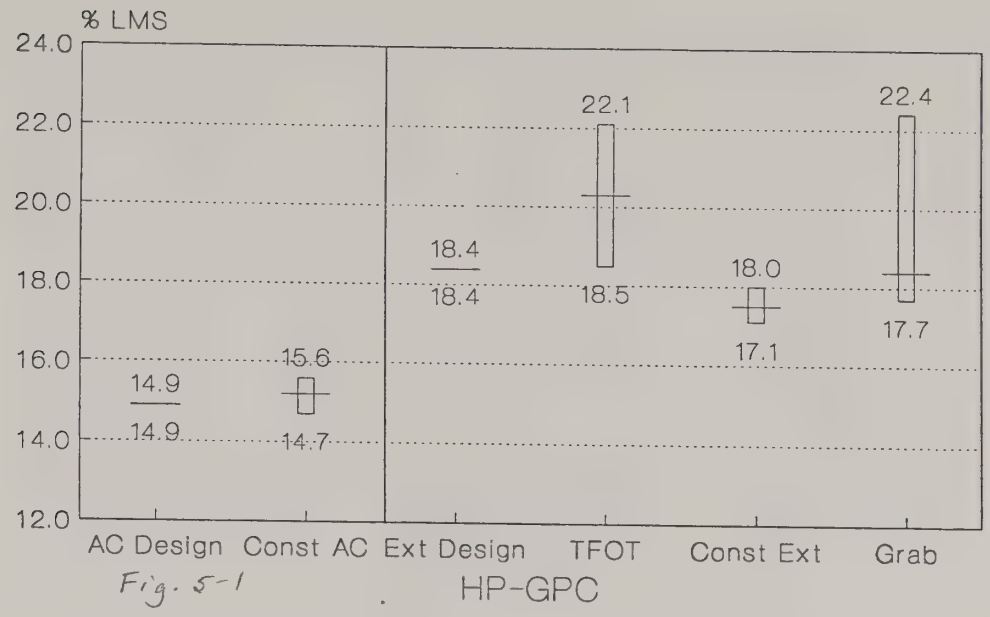


Fig. 5-1

HP-GPC

Bloomfield

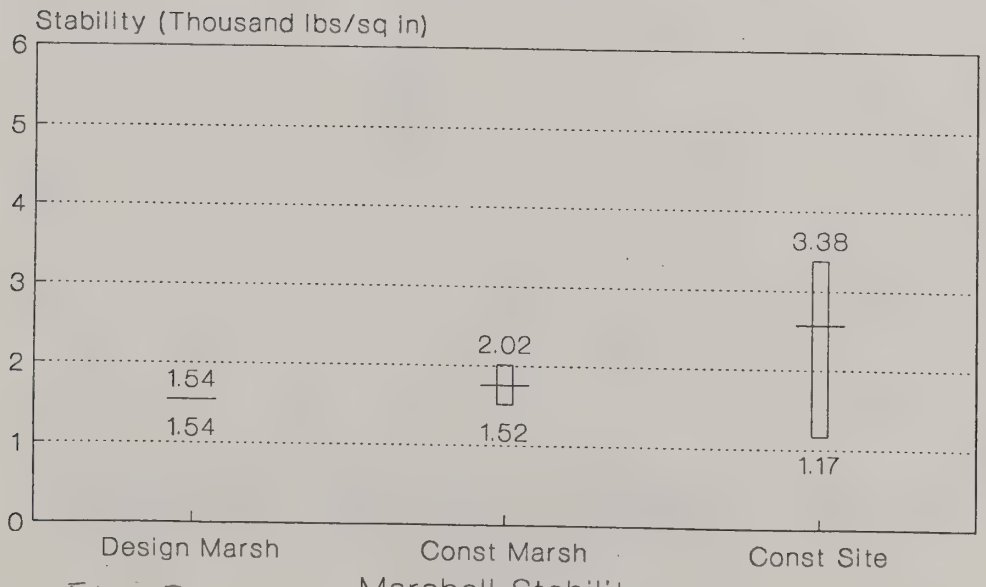


Fig. 5-2

Marshall Stability

Bloomfield

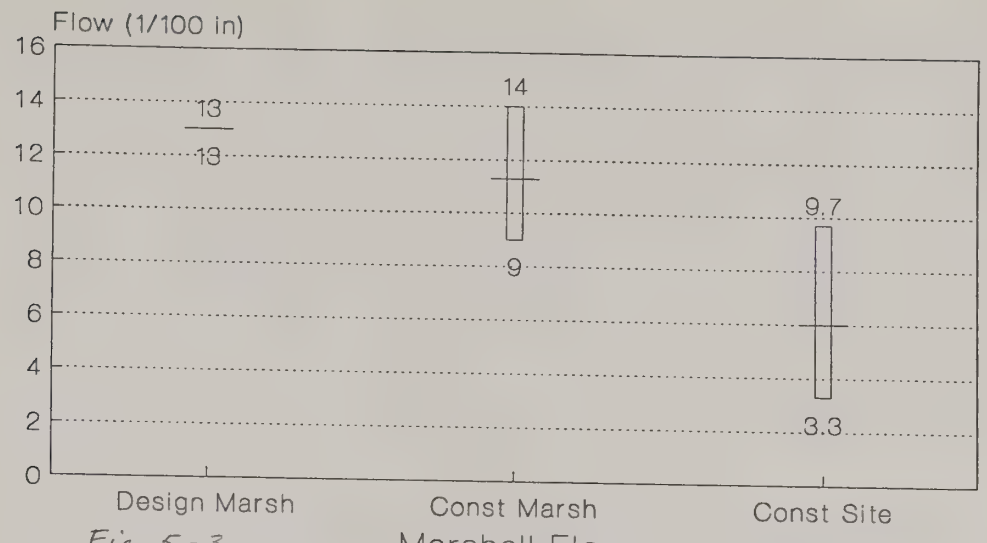


Fig. 5-3

Marshall Flow

Bloomfield

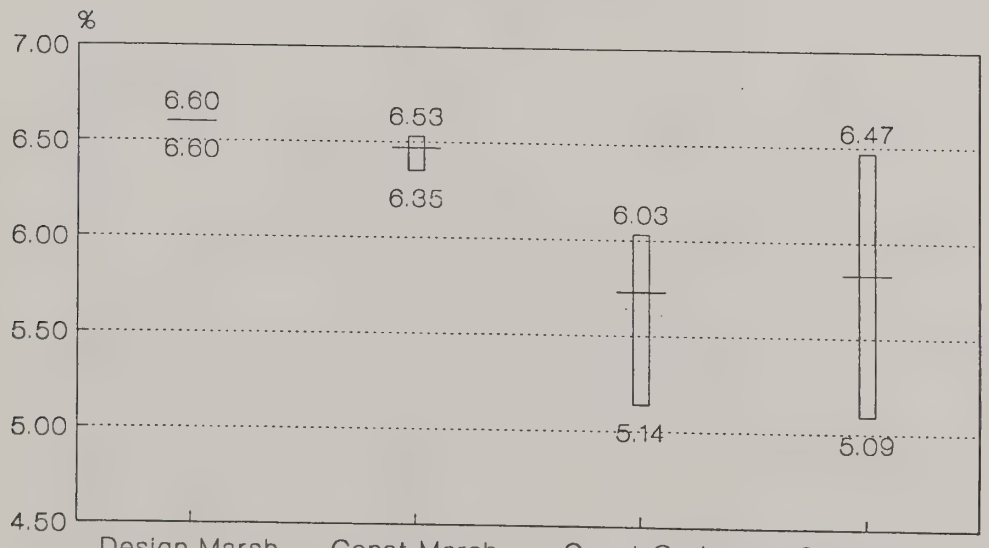


Fig. 5-4

% Asphalt Cement

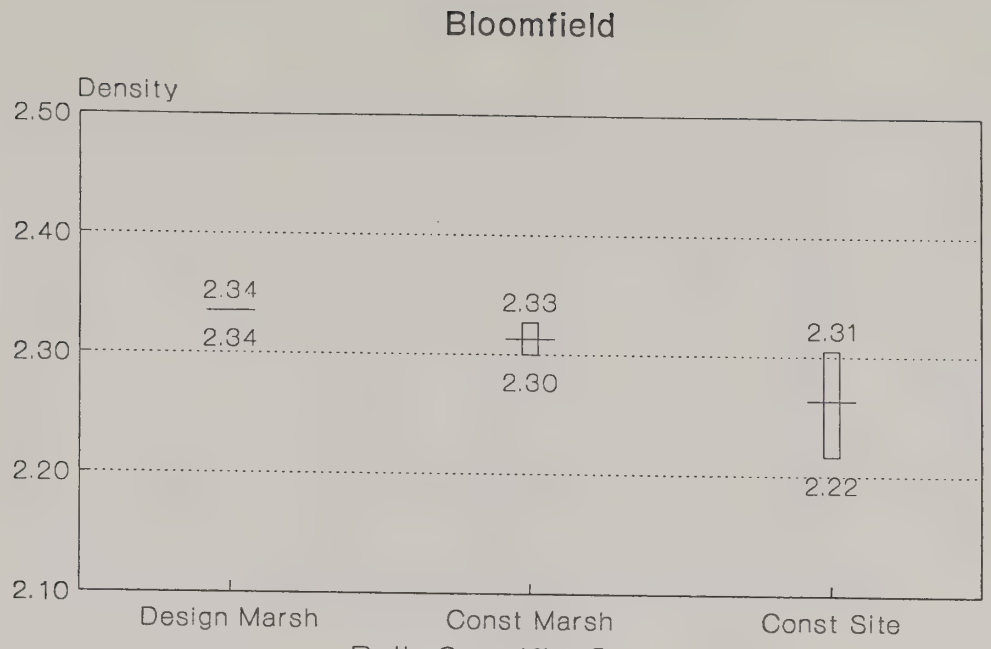


Fig. 5-5 Bulk Specific Gravity

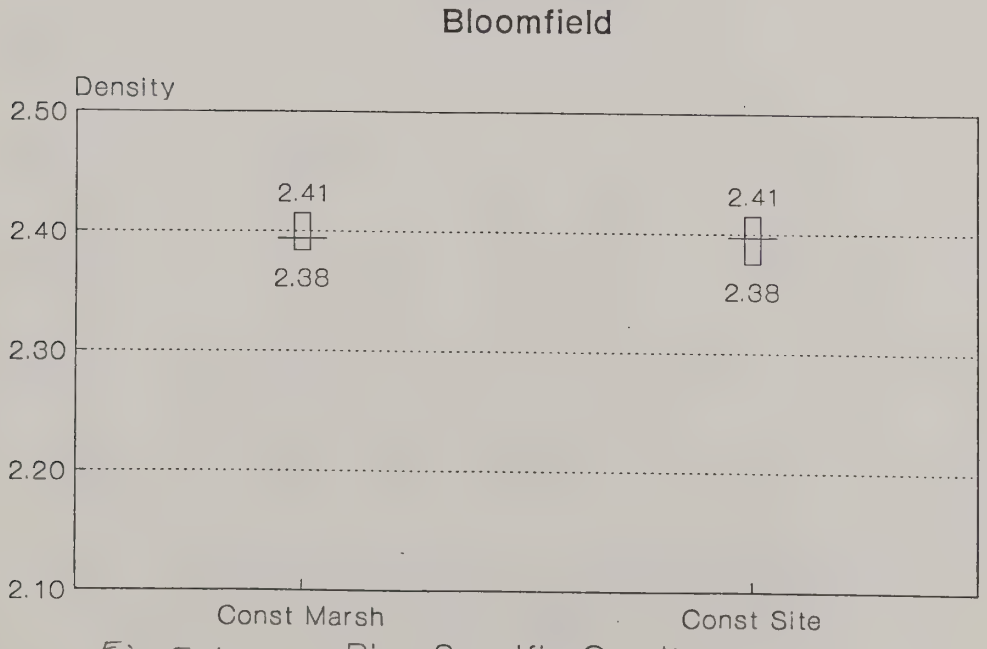


Fig 5-6 Rice Specific Gravity

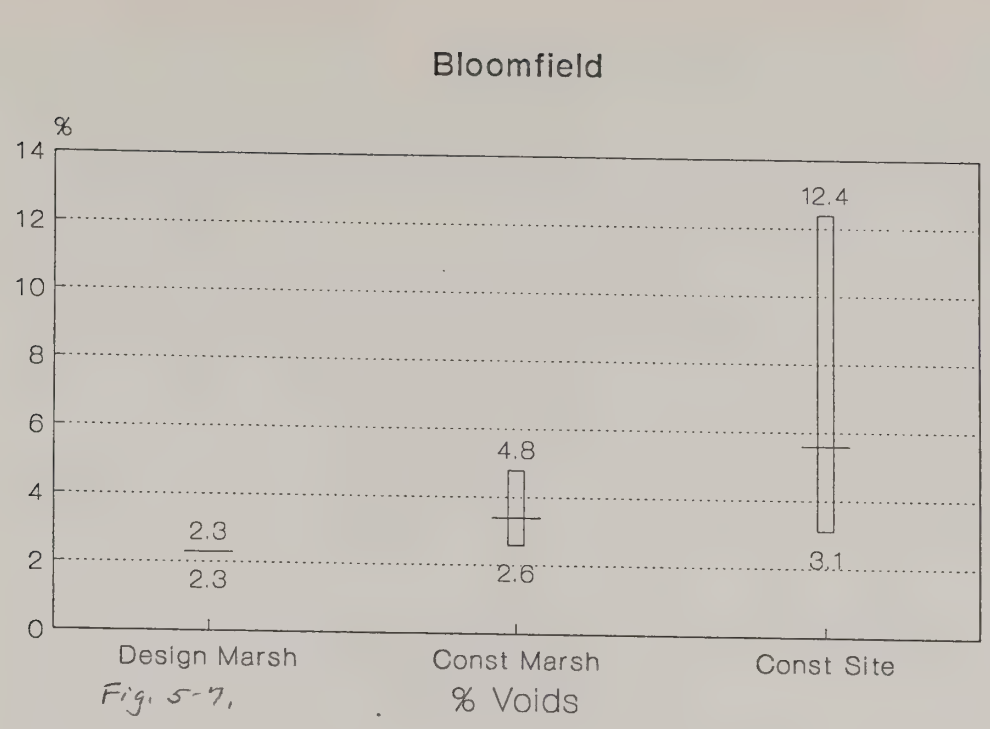

Bloomfield
%
14
12
10
8
6
4
2
0
12.4
4.8
2.3
2.3
2.6
3.1
Design Marsh
Const Marsh
Const Site
% Voids

Fig. 5-7.

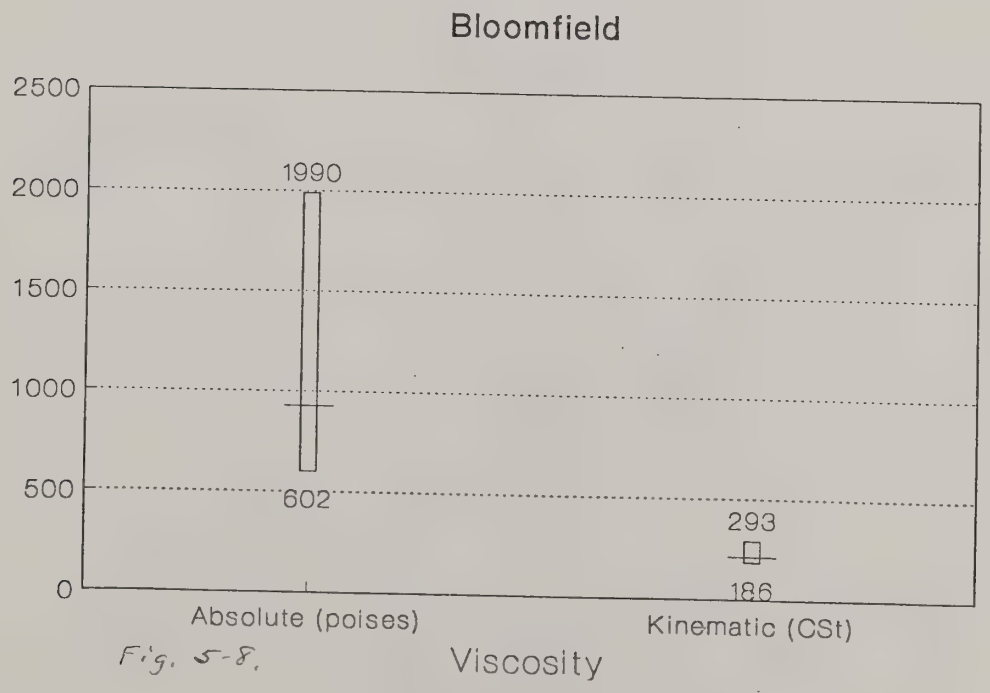

Bloomfield
2500
2000
1500
1000
500
0
1990
602
293
186
Absolute (poises)
Kinematic (CSt)
Viscosity

Fig. 5-8.

Bloomfield

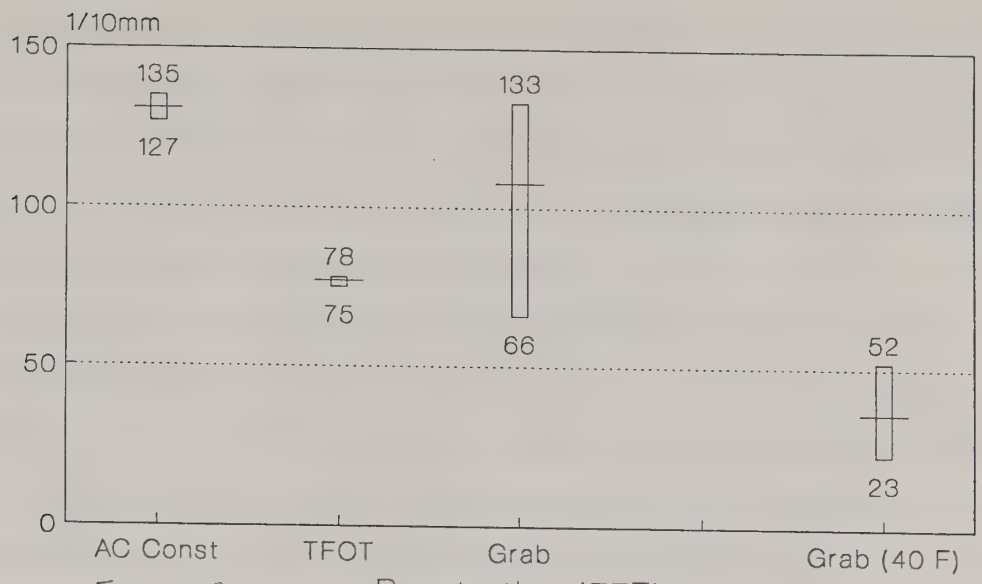


Fig. 5-9 Penetration (77F)

Bloomfield

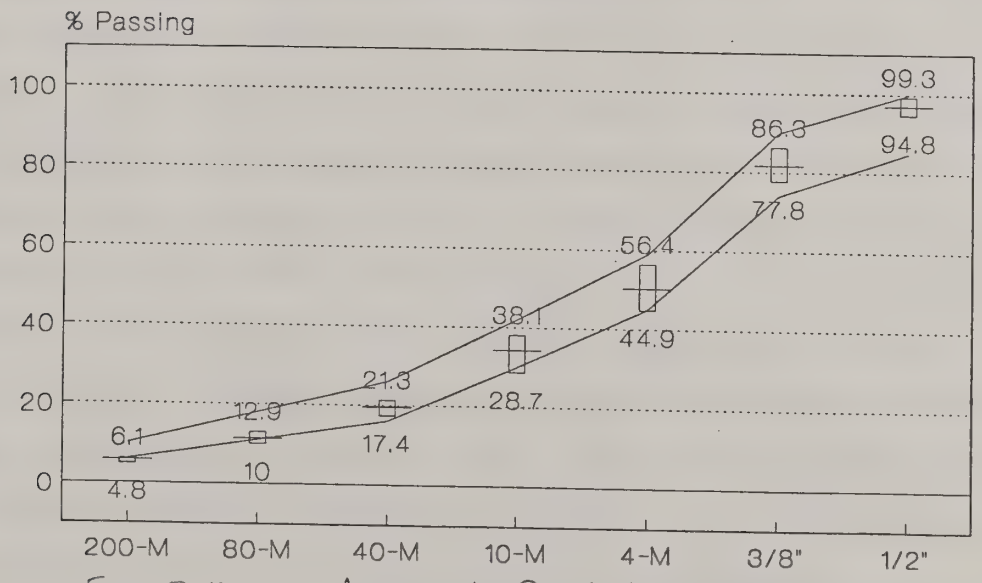


Fig. 5-10 Aggregate Gradations

Custer-East

Custer-East [IR 94-1(49)47] constructed with Exxon/85-100 over the period 1 August through 18 August 1988, was sampled the 15th through 17th of August. Reviewing the HP-GPC LMS percentage data in Figure 5-11 it is seen that the Construction AC average is slightly less than the AC Design.

The next set of four samples should have approximately the same LMS percentages. The LMS value for the Design Extract is decidedly lower than for TFOT or construction samples. This may reflect differences in the asphalt cement, the aggregate or the mix temperature between the design and construction. The TFOT accurately mirrors the construction extract from field Marshall specimens, but the grab samples show a significantly wider range and an average of 2% more LMS.

Both Marshall stability and flow are highly variable for Construction site samples as seen in Figures 5-12 and 5-13. In contrast, the Construction Marshall samples show a tight range for stability with a lower average value, and a comparable range but much higher average for flow. Other qualitative physical parameters show similar relationships as found in the Bloomfield project. Rice specific gravities are comparable but bulk gravities show a broad range which directly affects the broad range determined for percent voids. The range of voids in the mat is more than 9% although the average is 6%. Penetration and viscosity results have similar range characteristics.

Figure 5-14 compares asphalt cement percentages found in Construction Marshall samples with site and grab samples. Field laboratory prepared samples averaged 5.21% with 0.85% variability. Grab samples also averaged 5.21% but with a larger variability of 1.8%. Construction site samples have a slightly lower average, 4.9%, than the Construction Marshall with a similar range. These averages are much closer than comparable averages for Bloomfield.

Aggregate gradations are plotted in Figure 5-20 . The 3/8" and 1/2" sizes were found to fall below the minimum specification.

On the 15th and 16th of August, (sampling days), the hydrated lime was turned off for about fifteen minutes each day resulting in a few truck loads of mix without lime. Identification of areas and the effects of this difference on the mat, if any, are difficult to evaluate.

Custer

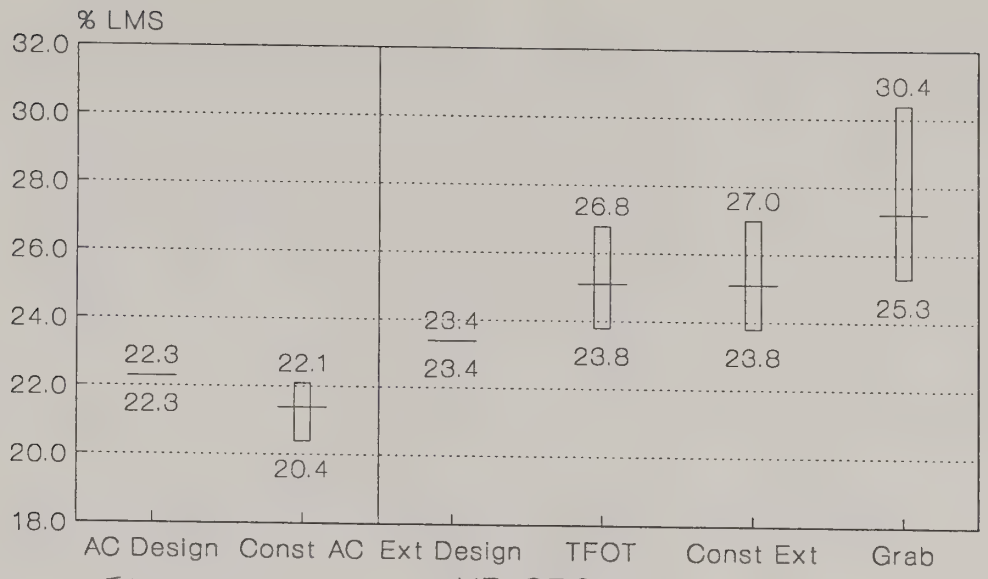


Fig. 5-11 HP-GPC

Custer

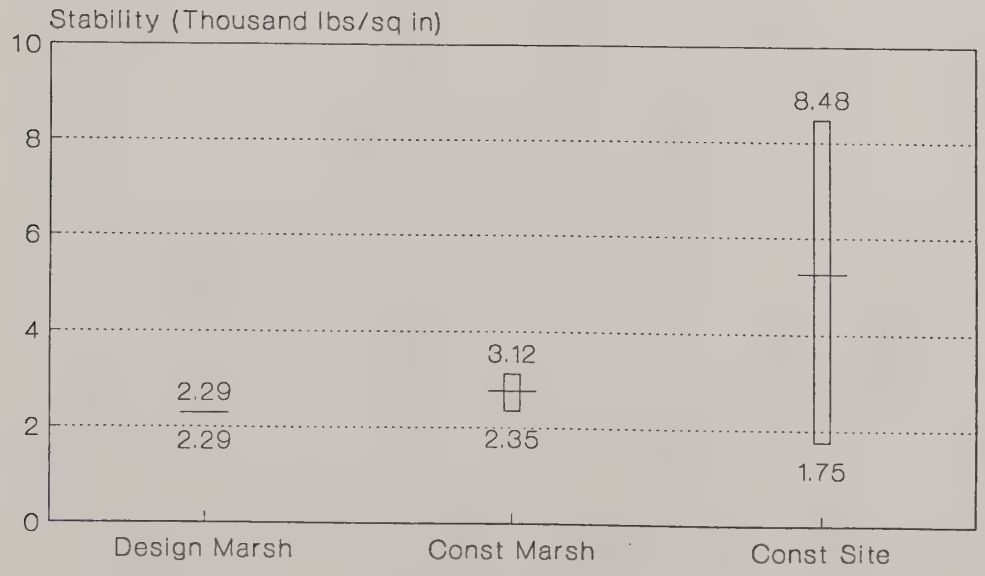


Fig. 5-12 Marshall Stability

Custer

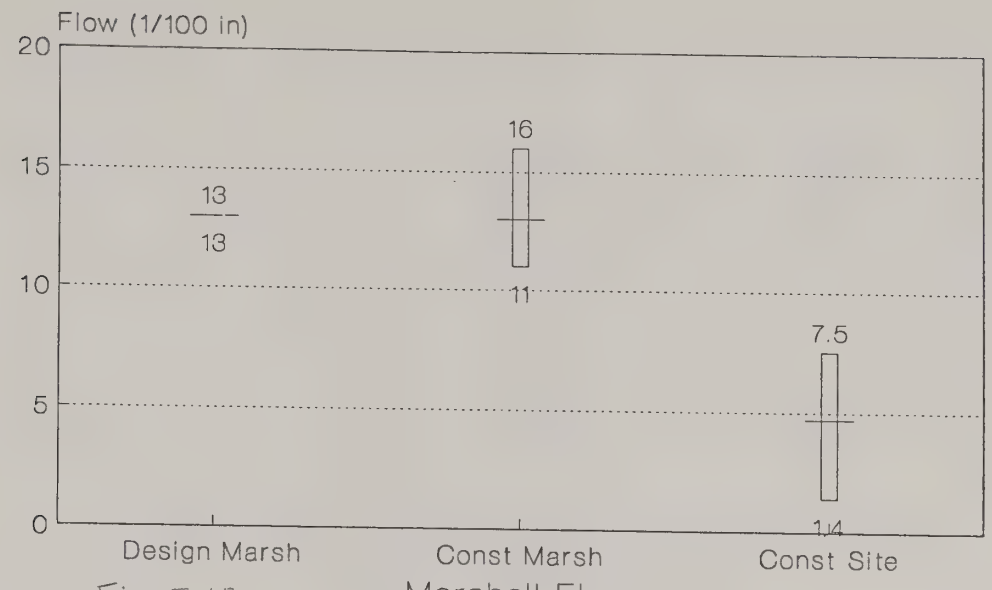


Fig 5-13. Marshall Flow

Custer

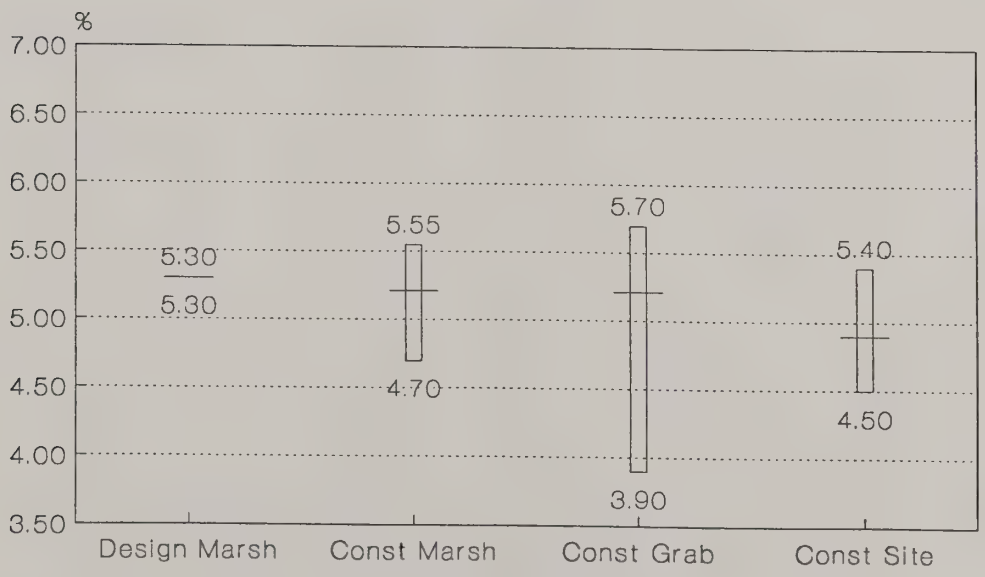


Fig 5-14. % Asphalt Cement

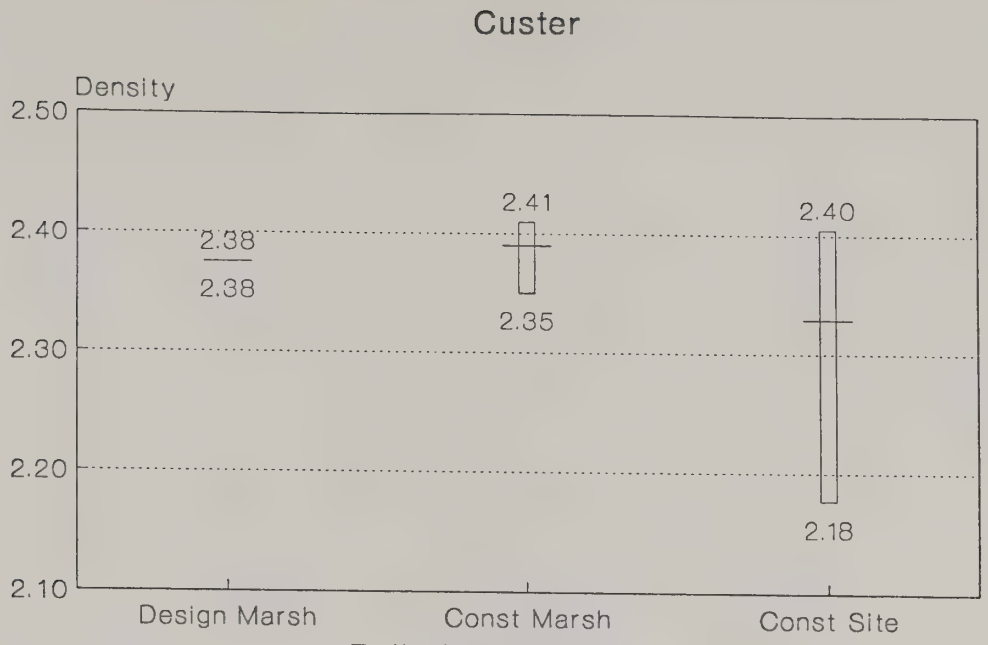


Fig. 5-15 Bulk Specific Gravity

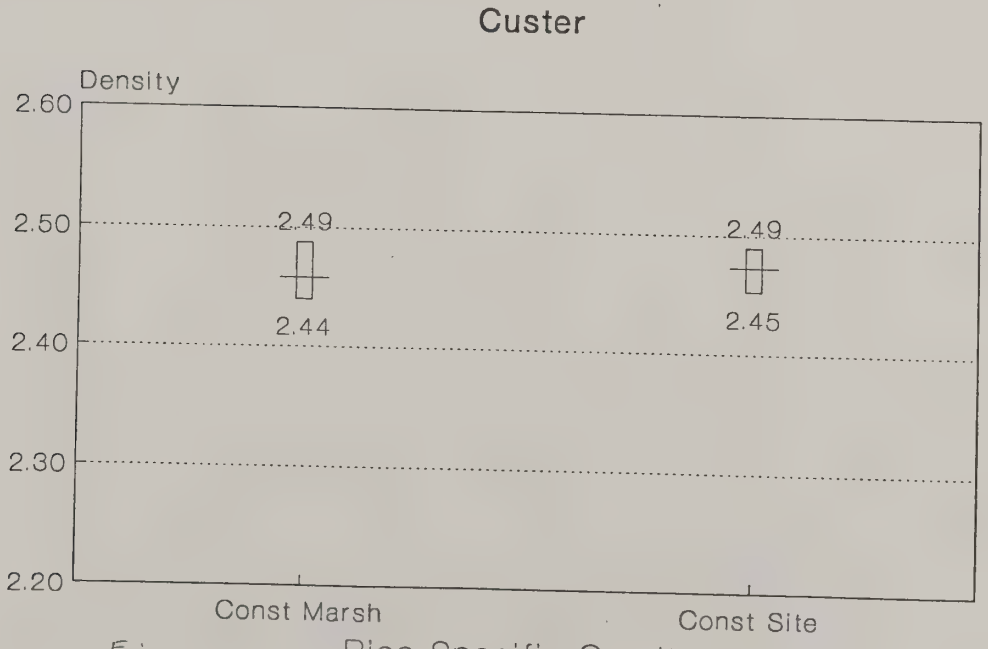


Fig 5-16 Rice Specific Gravity

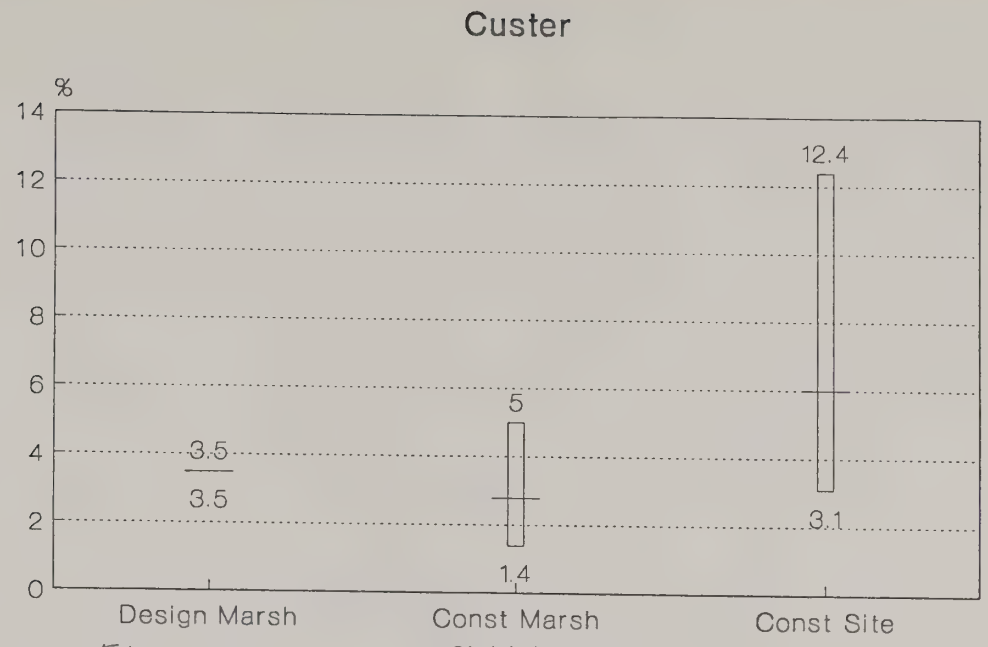


Fig 5-17 % Voids

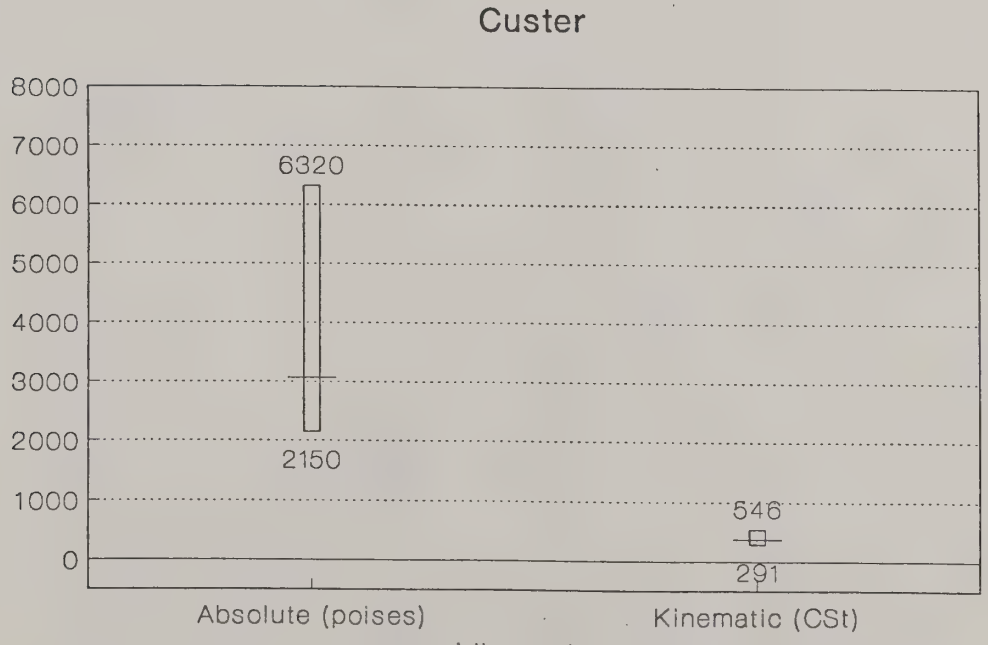


Fig 5-18 Viscosity

Custer

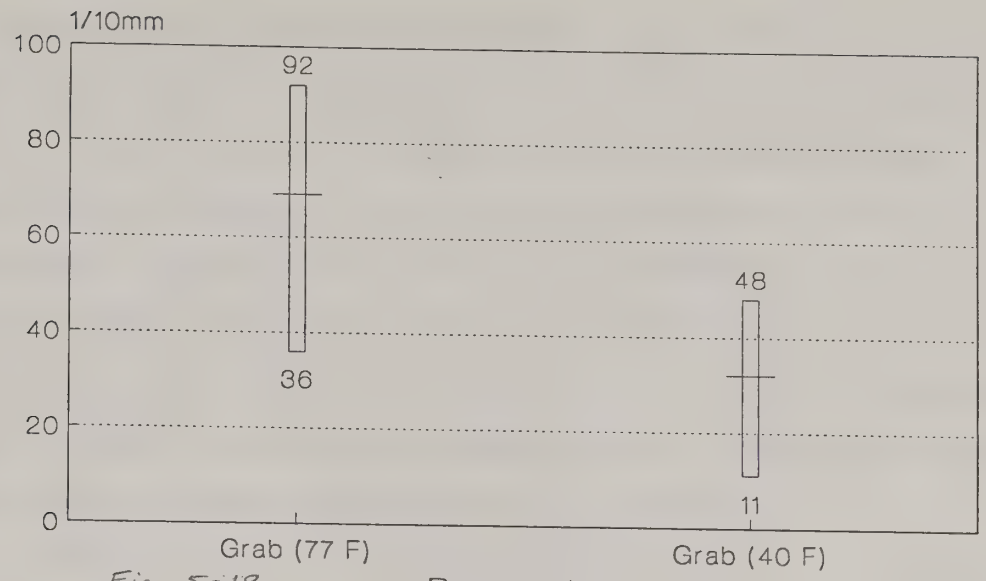


Fig. 5-19 Penetration

Custer

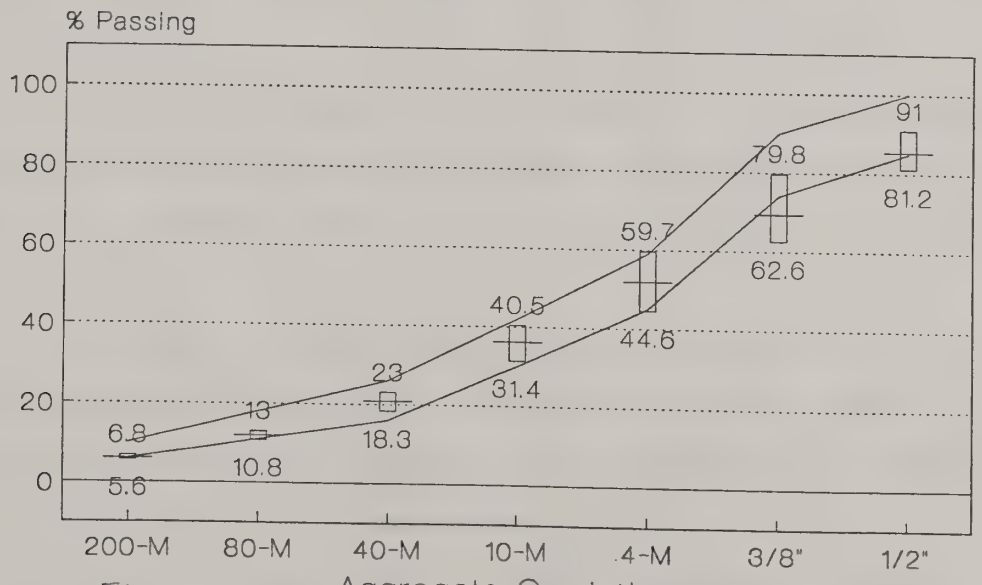


Fig. 5-20 Aggregate Gradations

Helena-West

Helena-West [RTF-BRF 8-2(15)34] constructed with Conoco/ 85-100 asphalt cement, was sampled on the 8th and 9th of October, 1988. HP-GPC results for this project are shown in Figure 5-21. AC Design and Construction AC sample averages are within reasonable range of each other as are averages for the next four sample types. The maximum shown for TFOT samples is considerably greater than the next lowest value which is more representative of the sample distribution, suggesting that the maximum may be due to some extreme TFOT analytical variable.

Marshall stability ranges for this project are much smaller relative to the other projects investigated. Figure 5-22 shows the average for Construction Marshall samples to be similar to that found in the site samples although the latter still have a two-fold range. Marshall flows for these sample sets likewise follow previous project trends, the Construction Marshall samples having higher flow values whereas those for the Construction site are several orders of magnitude lower. In this case the field laboratory prepared samples have a larger range than actual mat samples.

The asphalt contents have a range of just over 1% in the Construction Site samples and less than 1% in the other construction-generated samples. The averages of all three types are somewhat lower than the design target.

Rice specific gravities for the Construction Marshall and site samples are comparable, bulk specific gravities and void

percentages for the latter having, as expected, broad ranges as shown in Figures 5-25 through 5-27. Voids content of the mat has a large percentage range, the average is just under 10%. Penetration and viscosity data for the 85/100 asphalt cement recovered from the grab samples have relatively tighter ranges as seen in Figures 5-28 and 5-29.

In Figure 5-30 a number of aggregate sizes are shown to fall both below and above the specification range. Of the four projects investigated, this one contains the greatest number of non-compliance data points. A review of aggregate gradation field determinations by MDOH indicates that nearly all comply with the specification, excepting a few which were borderline. Differences found here may be due to mix processing which has resulted in limited fracturing of a less competent rock.

Helena

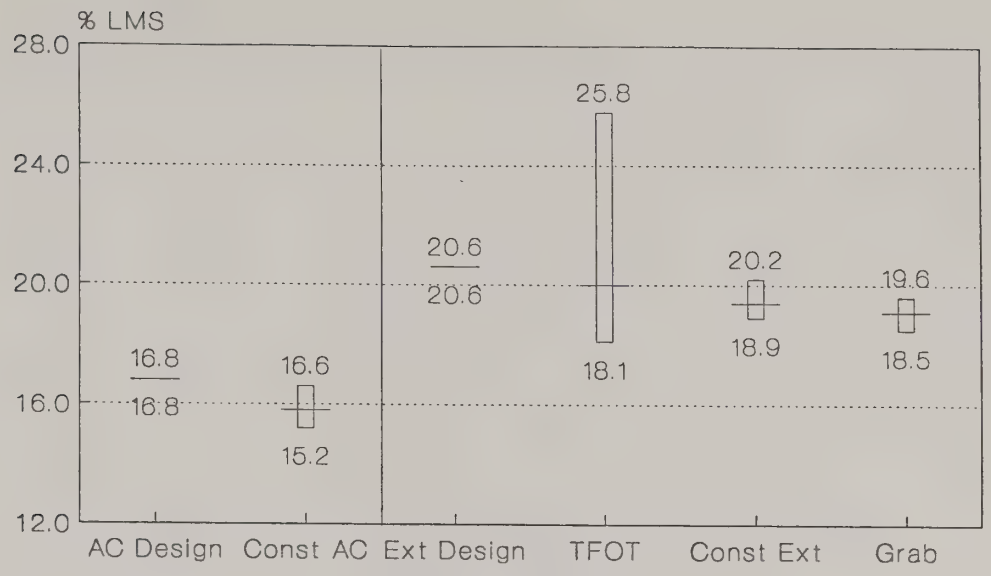


Fig. 5-21 HP-GPC

Helena

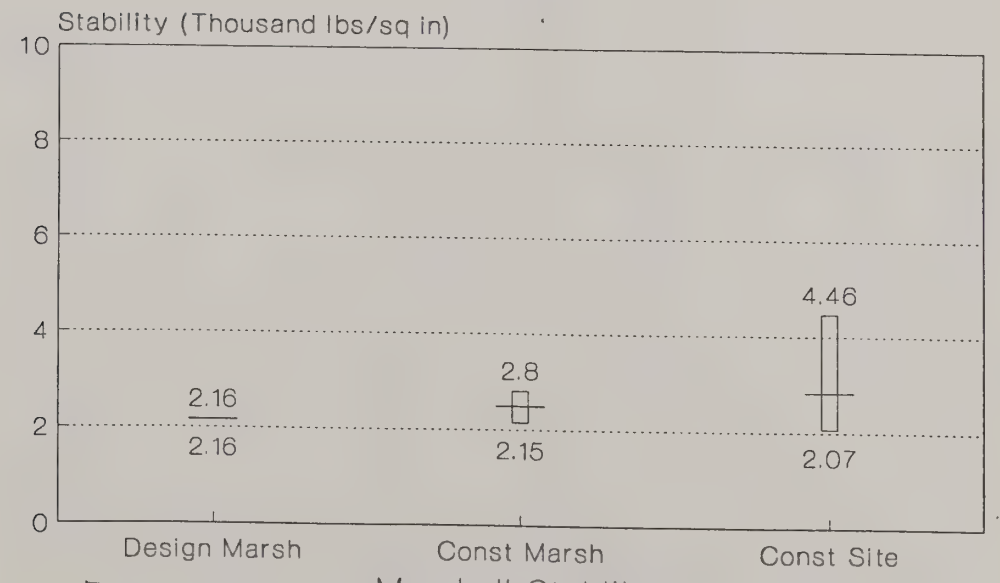


Fig 5-22 Marshall Stability

Helena

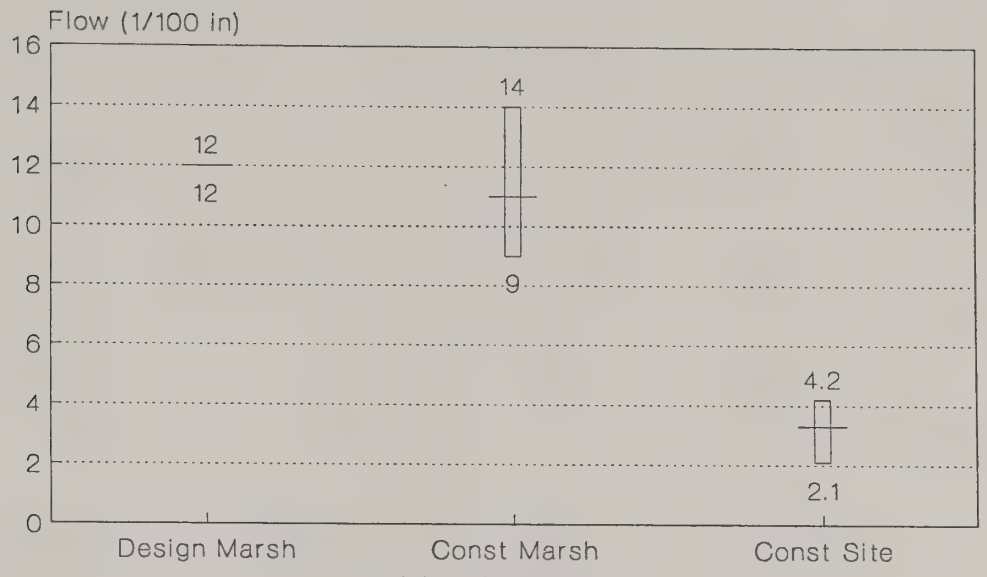


Fig 5-23 Marshall Flow

Helena

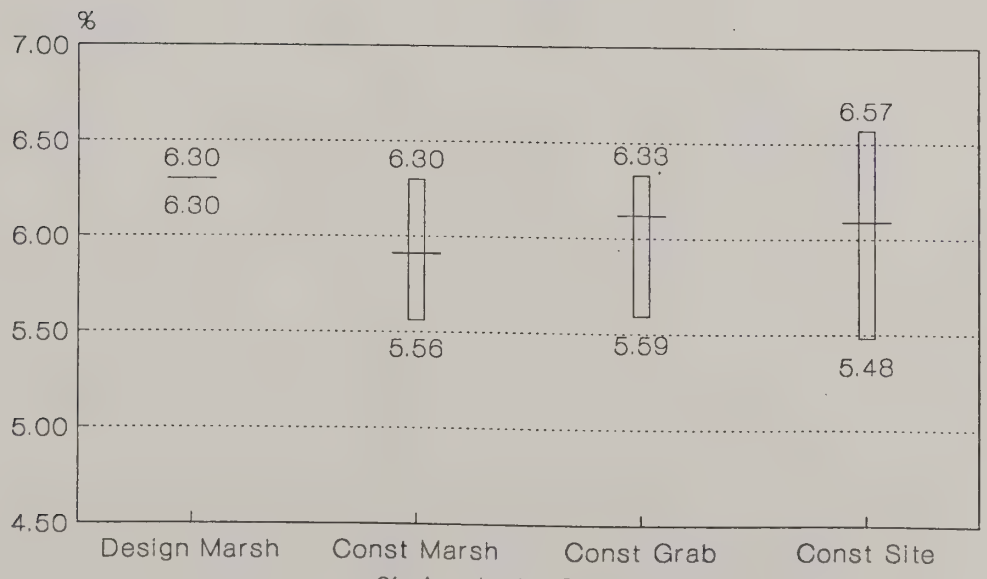


Fig. 5-24 % Asphalt Cement

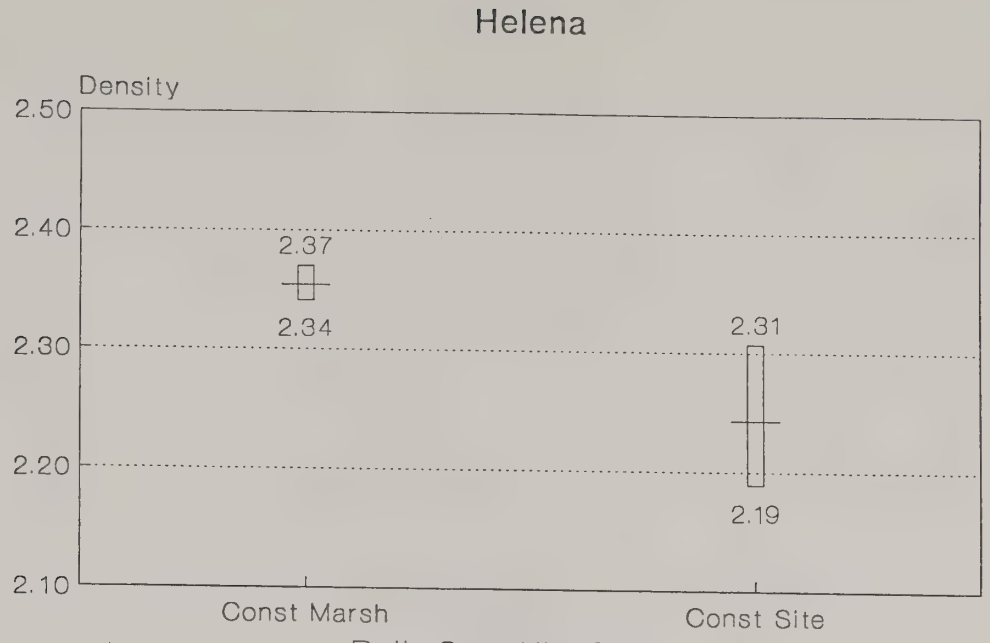


Fig. 5-25 Bulk Specific Gravity

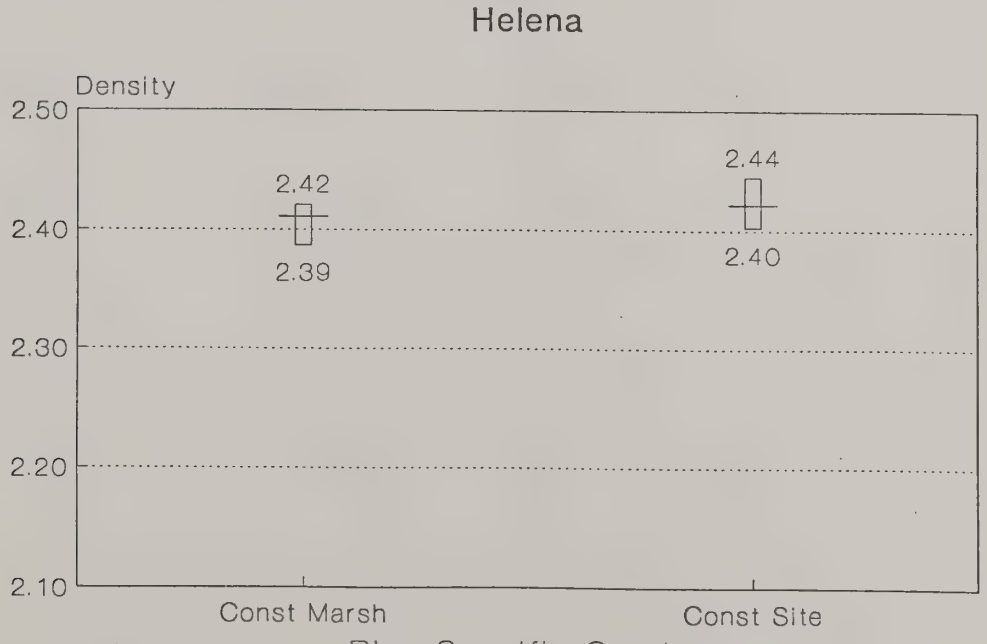


Fig 5-26 Rice Specific Gravity

Helena

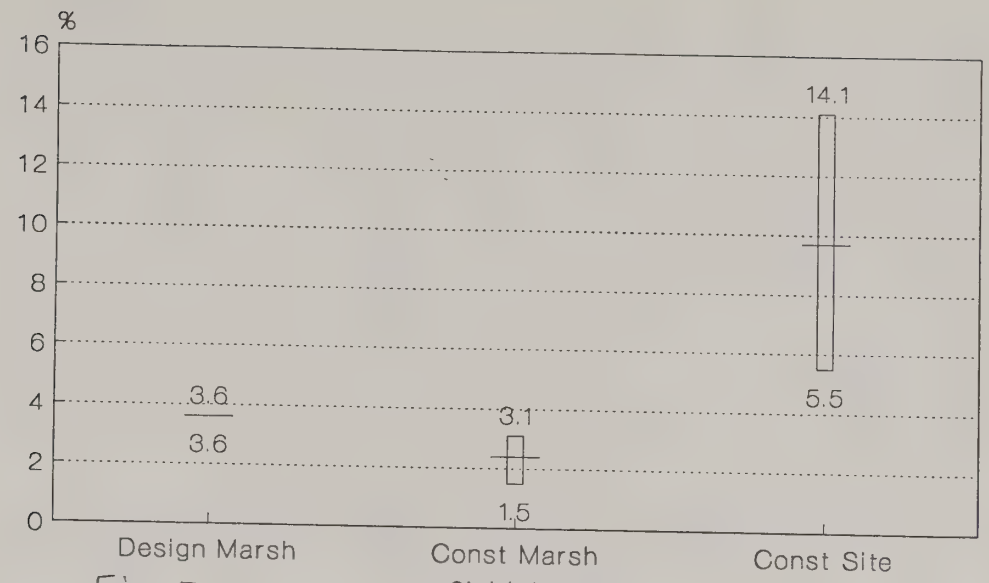


Fig 5-27 % Voids

Helena

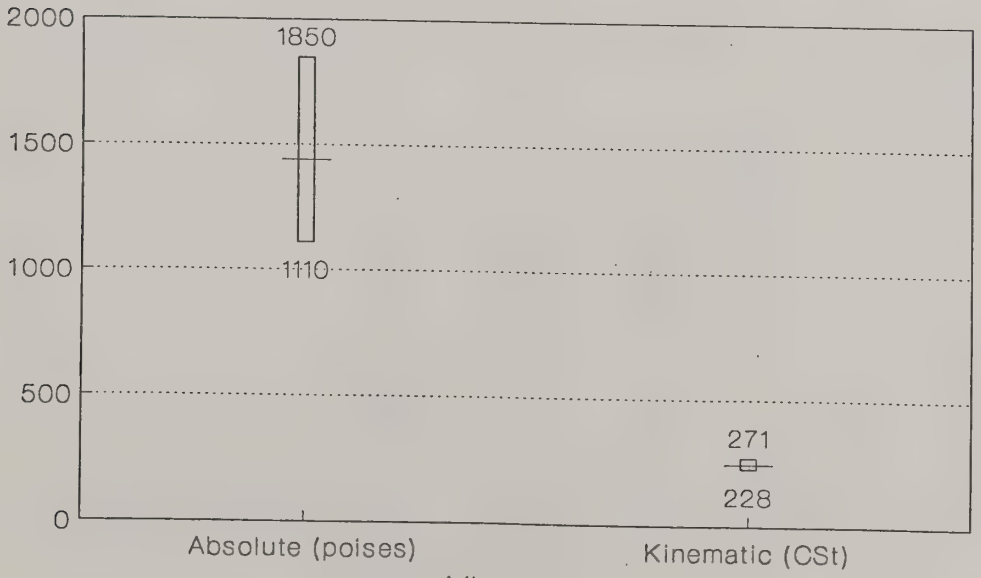


Fig 5-28 Viscosity

Helena

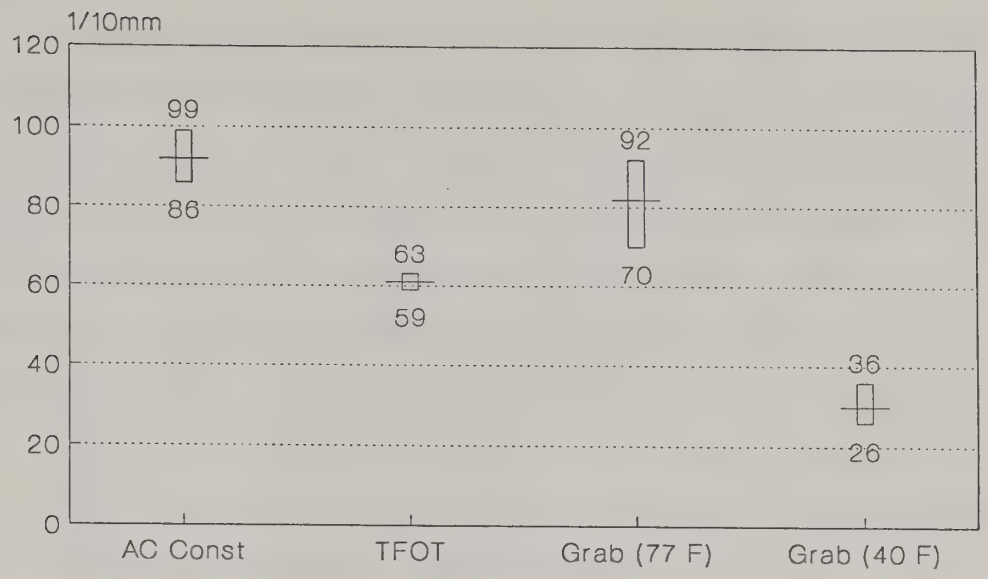


Fig. 5-29 Penetration

Helena

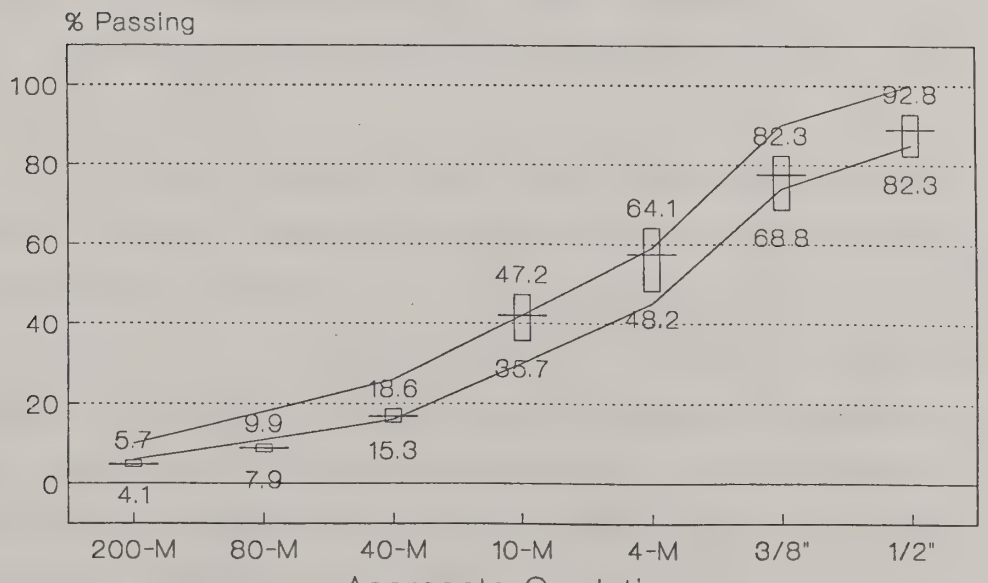


Fig 5-30 Aggregate Gradations

Potomac-West

Potomac-West, F-BHF 24-1(25)9, constructed with Montana Refining Company/85-100, was sampled on the 17th, 18th, and 24th of October, 1988. Beginning with the HP-GPC data for the various sample types shown in Figure 5-31, it is seen that the AC Design and Construction AC samples match fairly well and that the remaining four sample types display some variability. The TFOT sample set with a 4% range has the widest variability. Note that the averages for these sample sets are within about 1%.

As in the previously discussed projects, the Construction site samples are found to have Marshall stabilities and flows with a broad range of values, the Construction Marshall laboratory prepared pucks having ranges reflecting highly controlled conditions. The same is true for Rice and bulk specific gravities and percent voids, (Figures 5-32, 33, 35, 36, 37). The voids content of the mat has a wide range and an average above 7%.

The asphalt content found in the three sample types in Figure 5-34 once again shows the average content and range to be significantly different, the Construction Marshall having a much smaller range than pavement samples. The solvent recovered asphalt has penetration and viscosity properties shown in Figures 5-38 and 5-39. Here the average pen for the grab samples was 73 while that for the TFOT was 56 at 77 degrees F. AC Construction penetration averaged 88. Both viscosities show to a broad

range, the kinematic viscosity having approximately 25 percent variability.

In Figure 5-40, the aggregate gradations are shown to be on the lower edge of the specification range, and the averages of the amounts passing the 3/8 and 1/2 inch screens to be below the target.

Potomac

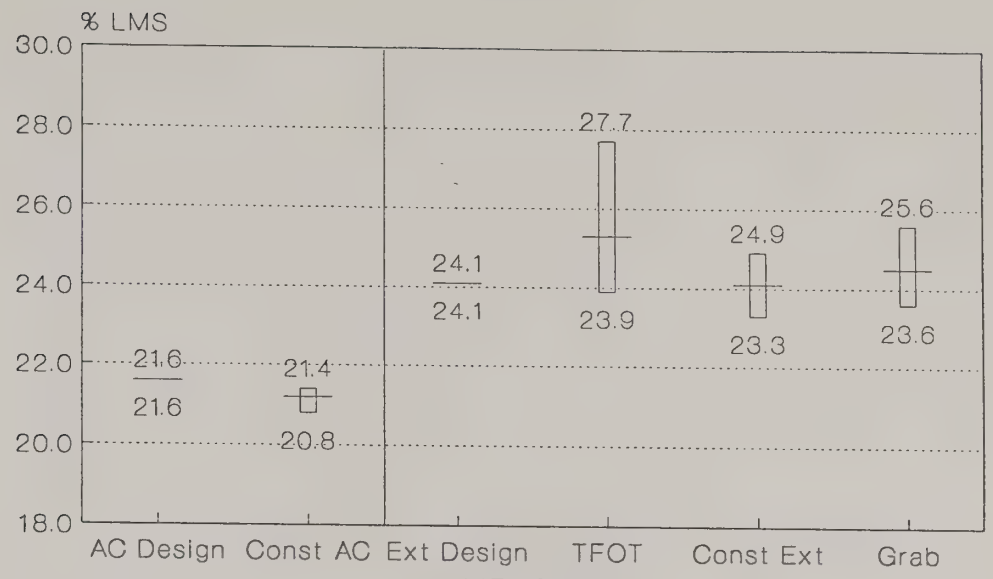


Fig 5-31

HP-GPC

Potomac

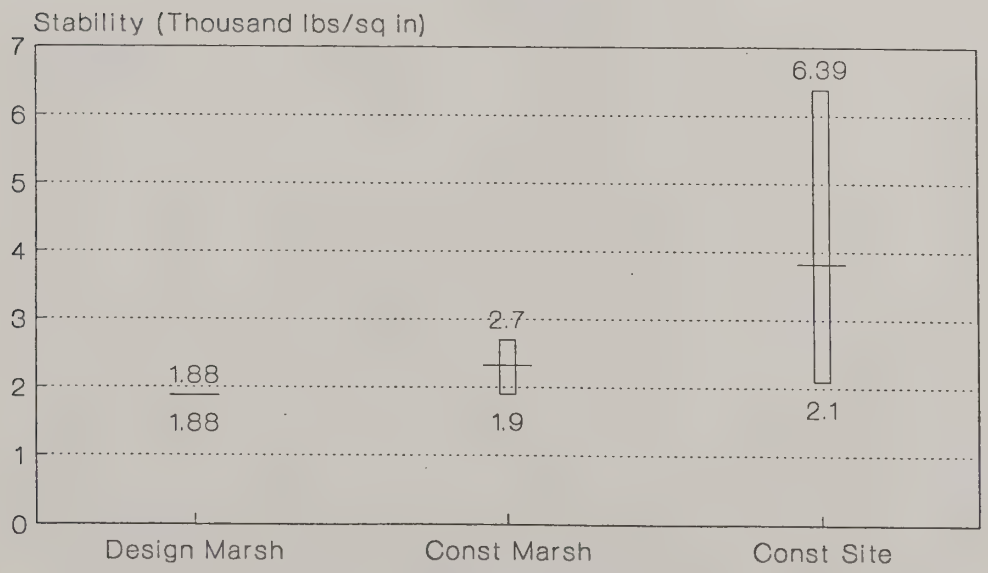


Fig 5-32

Marshall Stability

Potomac

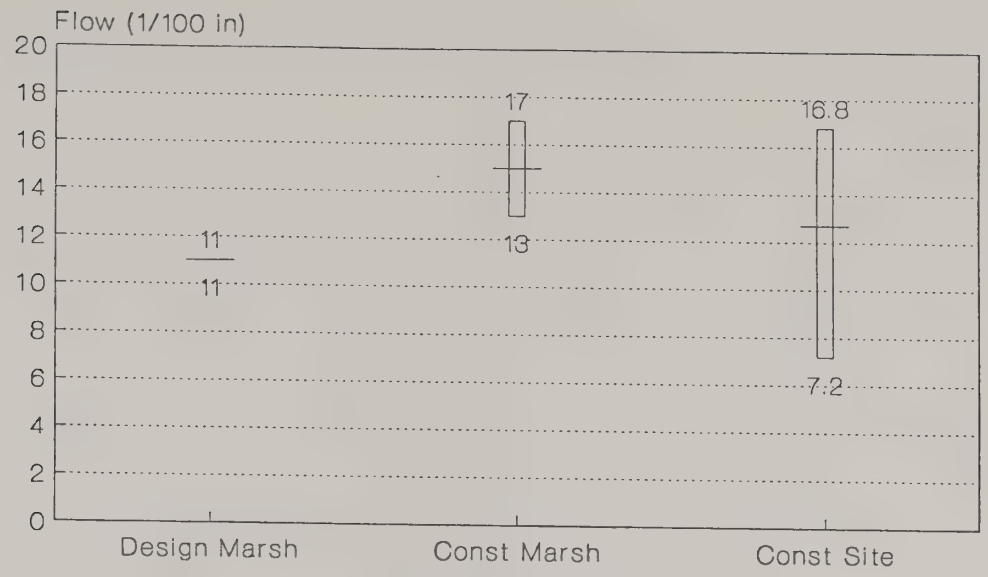


Fig. 5-33 Marshall Flow

Potomac

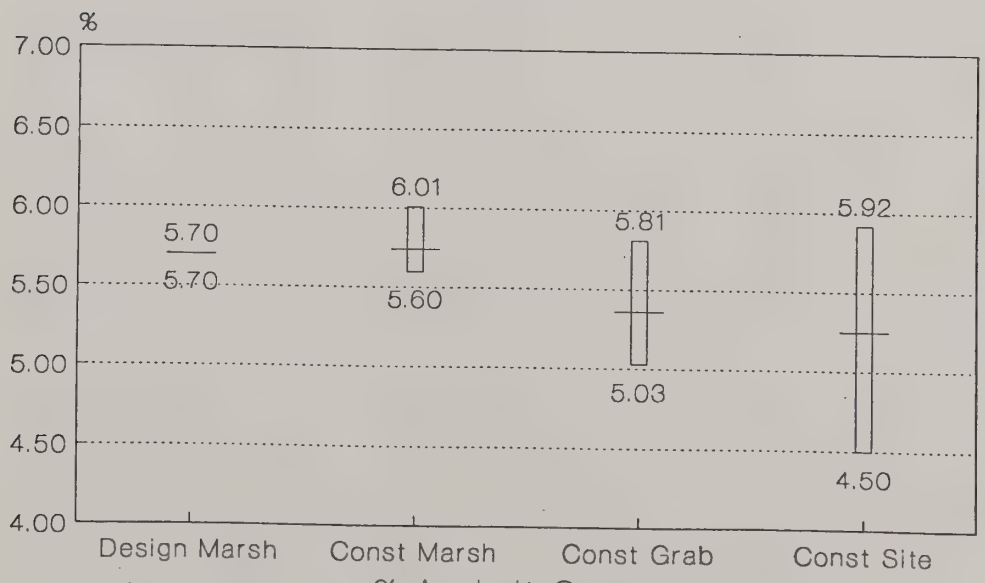


Fig 5-34 % Asphalt Cement

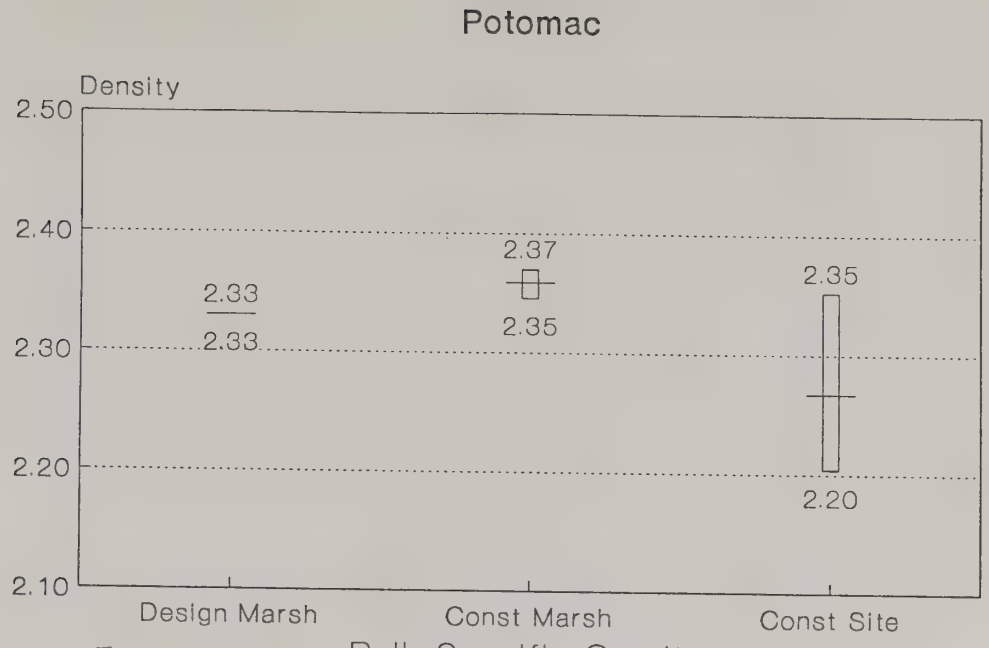


Fig. 5-35 Bulk Specific Gravity

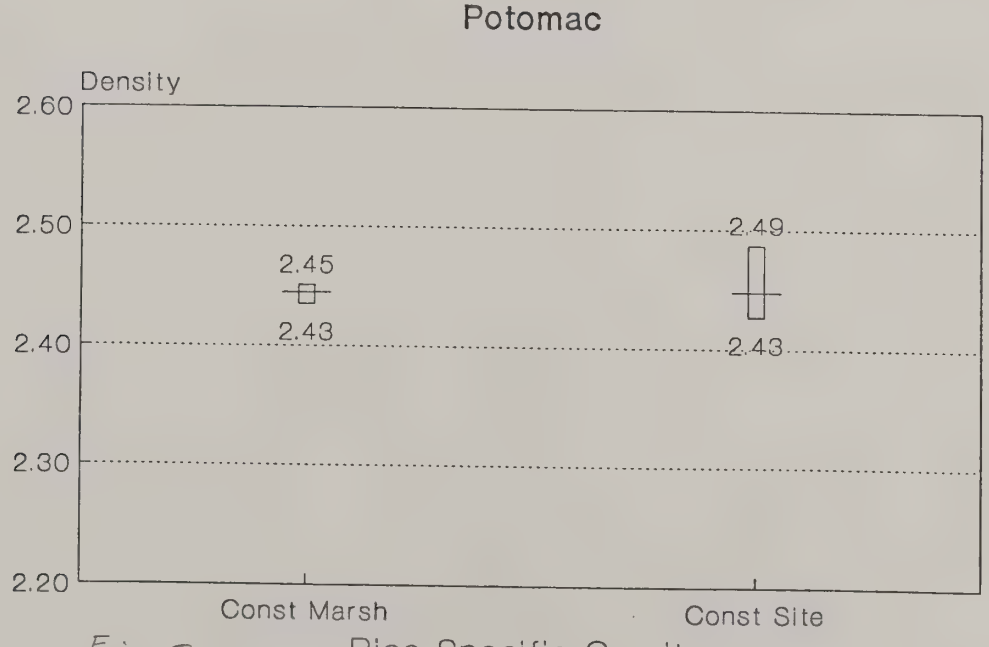


Fig. 5-36 Rice Specific Gravity

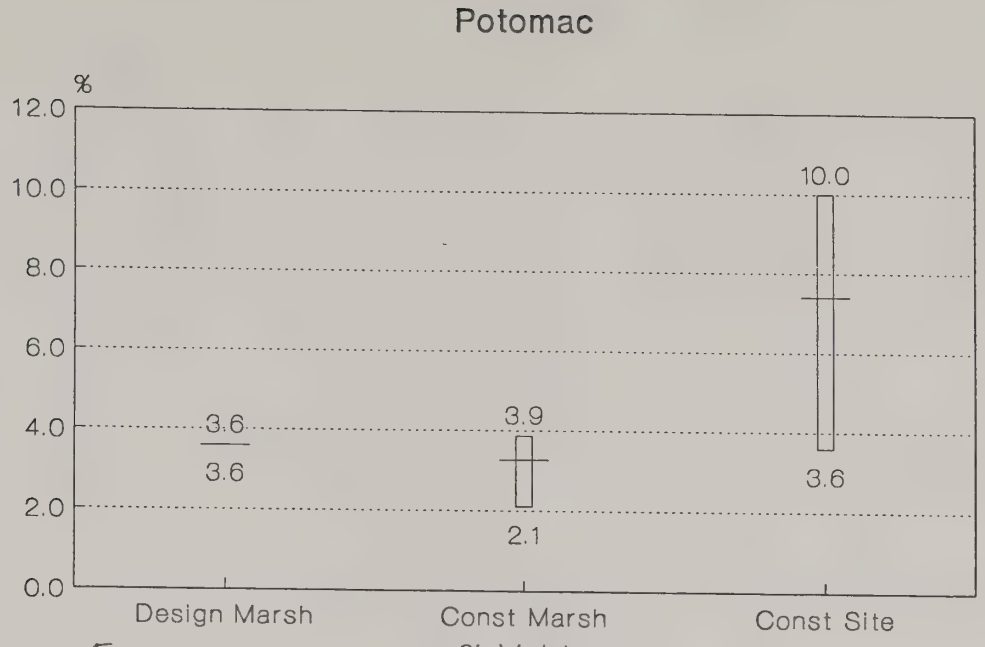


Fig. 5-37.

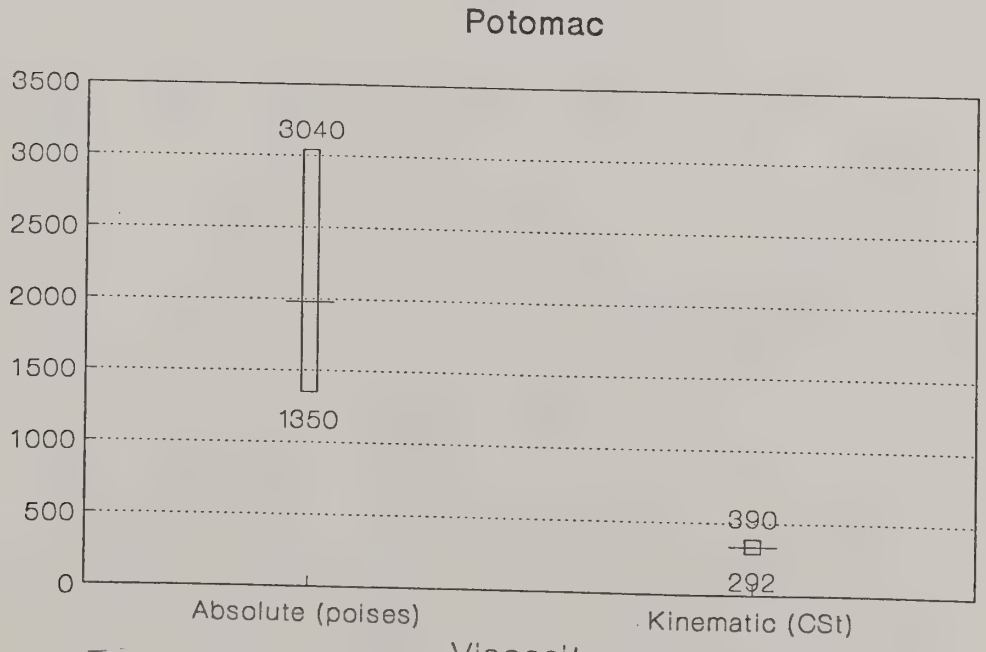


Fig. 5-38.

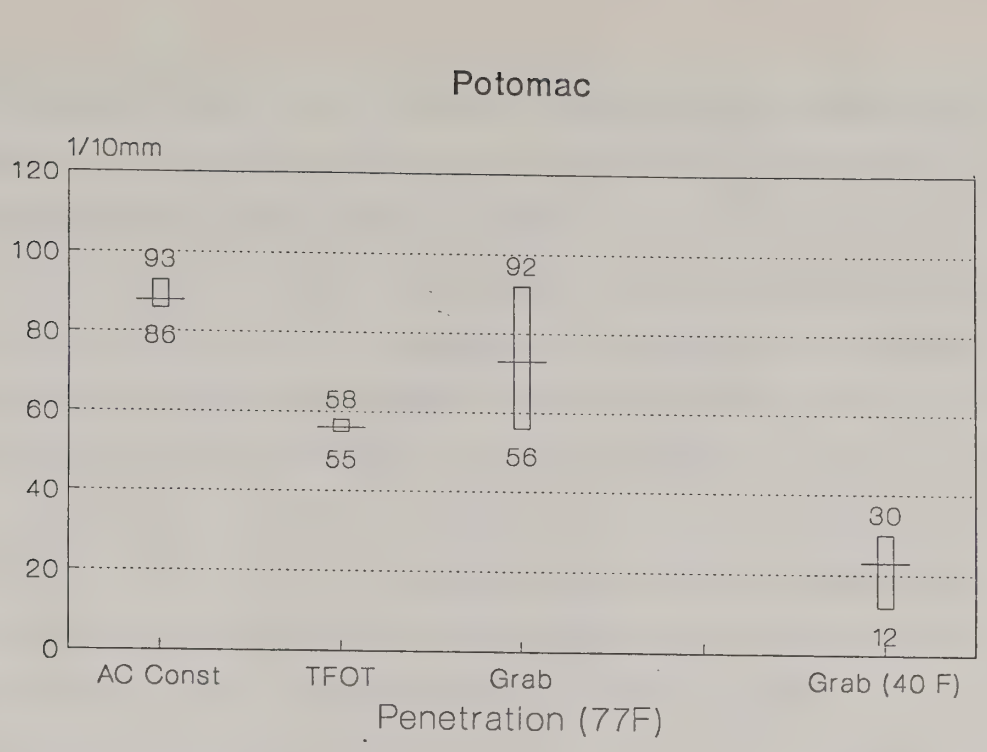


Fig. 5-39.

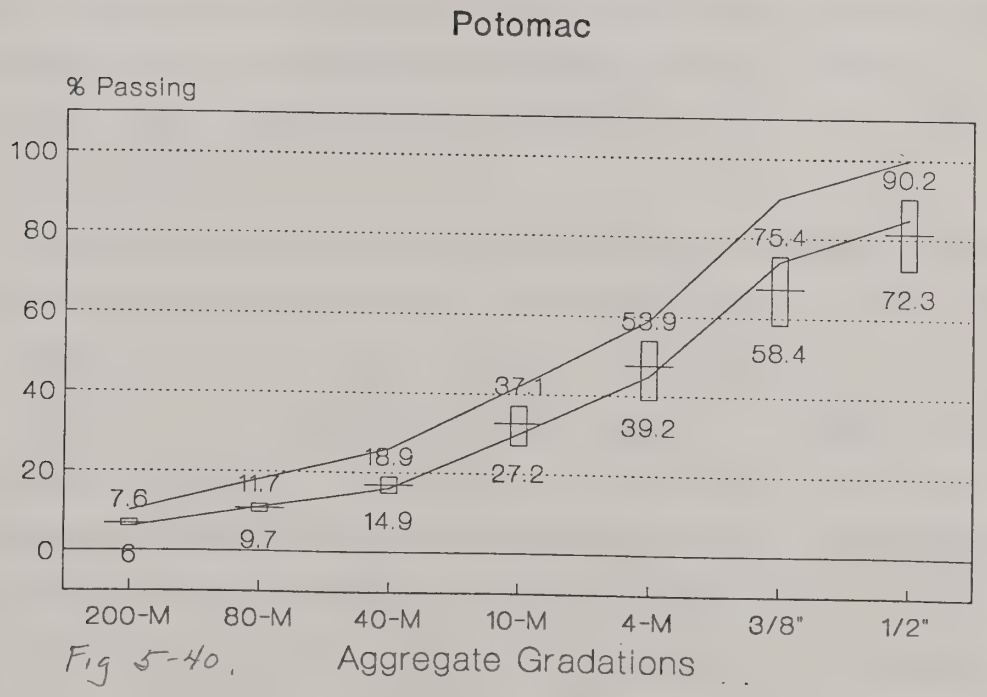


Fig 5-40.

The pattern for site samples (Figure 5-1) in these four projects was designed so that variability over both short and longer distances paved within 2-3 days could be monitored. Variability over the full observation period has been discussed; the following section will address the variability at shorter range. Differences in parameters from the center of the paver to about 1.5 to 2 feet from the edge of the paver will be inspected for evidence of paver-associated variability. The range of parameter values within the approximately 200-250 square feet of a single site will be studied for evidence of other sources of segregation as well as the variability that can affect perceptions of mat quality. Data will be found in Appendix B.

On the Bloomfield project, the range of Marshall stabilities in the roadway cores is 1170 to 3380 pounds, a nearly three-fold difference. There is no center-to-edge pattern. Within individual sites, the four samples differ by as little as 520 to as much as 2000 pounds.

Voids content on the project as a whole is between 3.6 and 7.4% for a difference of 3.8%. Differences among the four cores from single sites are as small as 1% but as large as 3.3%. In 8 of 12 cases, the voids content in the "center" is lower than at the adjacent "edge."

Asphalt content (MSU extractions) during the time monitored at Bloomfield range from 5.09 to 6.47% - a difference of about 1.4%. Within sets of four samples at a site, the differences in asphalt content varies from 0.43% to 1.4%; that is, the range for

the entire sampling actually occurs within one 250 square foot area.

Adjacent pairs (i.e., a "center" sample and its adjacent "edge" sample, have been scrutinized for evidence of segregation in the mix. At Bloomfield, seven adjacent pairs have asphalt contents which differ by 0.3% or more. In five of these pairs the higher asphalt content is in the "edge" sample. There are also differences, center-to-edge, in the aggregate gradation but those do not appear to follow a pattern.

Samples from the Helena-West project contain 5.5 to 14.1% voids, a range of 8.6%. Differences within the sets of four samples (from approximately 250 square feet) range from 4.3 to 5.7%. Voids content differences in adjacent pairs are as small as 0.1% to a maximum of 5.7%. In this project in only one case are the center-to-edge differences in voids content below 2%, however. Nevertheless, there is no pattern to this variability.

Asphalt content overall ranges from 5.48 to 6.57%--about 1.1%, reflecting good control. There is no center-to-edge pattern.

There are, however, substantial center-to-edge differences in aggregate gradation, particularly in the amounts retained on the 3/8 inch, 10M and 40M screens. In these cases there is often a concommitant difference in asphalt content such that the higher asphalt content is found in the samples with relatively more material retained on the 10M and 40M screens. This makes good sense, of course, since smaller materials have more surface area

per unit of volume to be coated with asphalt. Because of the close proximity of the differing samples, this may be regarded as evidence for segregation. However, since there is no center-to-edge pattern it does not appear that the paver is the source of the variability. In center-to-edge pairs with very similar asphalt contents, the differences in gradation are also small or are confined to and adjusted within two adjacent screen sizes.

Segregation is often visible in a freshly paved surface as very smooth areas, devoid of larger aggregate. In this project, no such areas were observed.

Marshall Test results from cores from the Potomac project range from 2100 to 6390 pounds, again about a three-fold difference. The differences within sets of four samples are found to be 660 to 3170 pounds. There is no center-to-edge pattern but differences in strength between samples in adjacent pairs range from 120 to 3040 pounds.

At Potomac, voids content ranges from 3.6 to 10.0% overall, a difference of 6.4%. Differences within groups of four samples range from 0.7 to 5.6% and, between adjacent pairs, from 0 to 3.9%. There is no center-to-edge pattern.

Asphalt content during the observation period ranges from 4.5 to 5.9%, a difference of 1.4%. Differences between adjacent samples range from 0.1 to 0.9% with no center-to-edge pattern and little relationship to aggregate gradation. In fact, with only a couple of exceptions, aggregate gradations are very similar between adjacent samples.

In the Custer pavement, Marshall stabilities are found to range between 1750 and 8480, a nearly 5-fold difference. There is no center-to-edge pattern but differences between adjacent samples range from 990 to 3950 pounds.

The range of asphalt content is 4.5 to 5.4% overall. In only four adjacent pairs is the difference in asphalt content more than 0.2%. The apparent association of asphalt content with aggregate gradation seen elsewhere is not apparent here. However, the gradations often show significant differences from center-to-edge.

Voids content ranges from 3.1 to 10.9% with no center-to-edge pattern. However, there are often large differences between adjacent samples (range 0.1 to 6.9%). And, in fact, the differences in voids content within site groups of four cores are at least 2.5% to as much as 6.9%.

Summary of Task 5.

Marshall Stability and flow. In general, Marshall stabilities have much larger ranges and higher values in the pavement than in the conditions of the on-site testing laboratory. Flow values show large differences as well. The wide range in the pavement is likely to stem from a number of sources including the operation of the roller.

Asphalt content also usually shows a broader range when determined by extraction than when determined by nuclear instrument. The averages are sometimes similar. Nevertheless,

this important parameter may still not be well enough controlled, especially considering its bearing on the rutting phenomenon. The difference between design asphalt content and that found in the field is legendary and evidence for it is seen here, with field AC% often being lower than design.

The variability in voids content, even between samples in close proximity, comes as somewhat of a surprise. With such variability, finding relationships with performance will be very difficult. It has been suggested that the variability may itself be a source of distress!

Evidence for segregation is scant although aggregate gradations do tend to wander in some projects within small areas of pavement and asphalt contents do in some cases tend to follow. In only one case (Bloomfield) is there any evidence for paver-associated segregation. Otherwise any segregation arises from undefined sources.

Task 7. Prediction of Pavement Performance

During the course of this and previous research projects, much work has been done to relate measureable properties with visible performance in pavements already in place. The purpose of this Task is to gather two more sets of data and then, if possible, to point out some ways in which all of this information may be used, not so much to <u>predict</u> pavement performance as to <u>improve</u> it. In this discussion, 1988 information about the Aging Study as well as 1988 data on the Test Sections will be

presented. Following those topics, means using the accumulated knowledge will be discussed.

The Aging Study

Beginning in 1976, a number of new pavements have been followed to trace their performance and to monitor changes in the HP-GPC characteristics of the asphalt cements. The pavements are now 7 to 12 years old. Most of them are overlays on primary, secondary and Interstate highways and two are urban highways. All Montana refineries are represented although Exxon asphalt is found in only one section.

In general the rutting performance observed in 1988 was quite good with rut depths less than 0.5 inch on 75% of the pavements. Cracking performance is not so encouraging, since 15 of the 21 pavements rated in 1988 are in poor to bad condition. Only two remain in excellent condition; one of these is an overlay. It is well known that reflection cracking in overlays is a serious problem but, because the condition of the underlying pavements is not known it can be only presumed that the present condition of the overlay mirrors the condition of the base. Nevertheless, it seems obvious that the solution to the problem of reflection cracking does not lie in the usual overlay procedures. It seems that no asphalt can withstand these pressures.

Cenex supplied asphalt cement for two overlays. One overlay paved with Cenex 200-300 grade AC and 21.2% LMS has deteriorated somewhat since the 1985 survey but remains in poor condition.

This secondary pavement shows negligible rutting. The LMS content has remained steady since construction. Another secondary roadway overlayed with Cenex 120-150 AC at 20.9% LMS remains in excellent condition after nine years.

Asphalt cement for eight overlays was received from Conoco. These surfaces are all in poor to bad condition, except one, which remains good after 9 years. Most of them were 120-150 grade; one construction used 85-100 and another 200-300, but no differences in performance are obvious.

One Exxon overlay is in poor condition. Of four overlays constructed with Phillips asphalt, two remain in good condition, two are "bad."

Data for the overlays is contained in Table 7-1. Although the total number of cracks has increased since the survey in 1985 (conducted by MDOH personnel), the performance ratings may not have changed. For the most part, the HP-GPC characteristics of the asphalt did not change appreciably through time. Exceptions are the Exxon asphalt which has apparently decreased 3% in LMS content, one Conoco asphalt which showed an increase of about 1.7% LMS and a Phillips which increased by 2.5% since construction.

Of the new (i.e., not overlay) pavements included in this group, one Cenex is in excellent condition after 9 years, another "bad"; a Conoco (200-300), is "poor," 2 Conoco (120-150) sections are bad, and one Phillips pavement is good to fair.

Overall, because of the diversity of these pavements and because most of them are overlays, it is not possible to draw performance-related generalizations. It is interesting to note that Phillips asphalts have shown quite good performance in two of four overlays and is only slowly cracking in a new pavement in spite of the high LMS content. It should also be noted that the nature of Cenex asphalt has changed (by HP-GPC characterization) and that the performance of the material often received presently may not be comparable to these earlier products.

Table 7-1. Aging Study Data

File	Pvmt. Age	Refiner	Grade	Hwy. type	Ruts '88	Crack* Rating '88	Crack** Rating '85	%LMS '88	%LMS constr.	Overlay ?
125	7	Cenex	200-300	2°	<0.25"	P	P	21.2	21.6	yes
70	9	Cenex	120-150	I	<0.5"	E	-	21.3	-	PMB
124	7	Cenex	120-150	I	<0.75"	B	G	20.8	21.6	no
65	9	Cenex	120-150	2°	<0.5"	E	E	-	20.9	yes
126	7	Conoco	85-100	Urban	<0.5"	P	P	-	19.0	yes
87	8	Conoco	120-150	1°	<0.5"	P	P	15.2	-	yes
64	9	Conoco	120-150	I	>0.75	G	G	15.8	17.1	yes
35 So	10	Conoco	120-150	1°	<0.25	B	B	-	20.8	yes
35 No	10	Conoco	120-150	1°	<0.75	B	B	-	18.9	yes
43	10	Conoco	200-300	1°	<0.25	P	P	17.7	-	no
4	10	Conoco	200-300	2°	<0.50	P	Fair	20.3	19.8	yes
97	11	Conoco	120-150	2°	<0.25	B	B	19.9	19.5	no
123	7	Conoco	120-150	1°	<0.25	P	P	18.9	17.2	yes
23	12	Conoco	120-150	I	<0.5	B	-	20.7	-	no
68	9	Exxon	120-150	I	<0.5	P	G	17.9	20.9	yes
90	8	Phillips	120-150	I	<0.5	G	G	24.0	24.1	yes
69	9	Phillips	120-150	1°	<0.25	G	E	-	25.5	yes
52	10	Phillips	120-150	1°	<0.5	B	E	-	24.3	yes
53	10	Phillips	85-100	Urban	<0.5	B	G	-	23.9	yes
122	7	Phillips	120-150	1°	<0.25	G-F	E	26.5	23.9	no

* E = Excellent; G = Good; P = Poor; B = Bad
** Rated by MDOH personnel.

The Test Sections

The Montana Test Sections near Big Timber continue to be a valuable source of information for this laboratory and the Montana Department of Highways. Their value stems from the facts that the construction was monitored and controlled and that the traffic loads and weather conditions are consistent over the entire project. After five years, a considerable amount of data has been collected and more trends have become obvious.

Since the last report on the Test Sections two performance observations have been made and one set of cores has been analyzed. In this section, the data and the trends now suggested will be discussed.

Figures 7-1 through 7-5 show in graphic form the performance of the various sections since their construction.

Note that the scale for crack counts on the left represents the total number of transverse cracks (full width, plus one lane wide, plus short cracks) in the 1200 foot test section. The rut depths are given in inches and represent the average of rut depths measured at each delineator in the section (3-4 measurements). Only driving lane figures are reported.

Rutting

Discussion of rutting will be by refinery but it should be kept in mind that asphalt content appears to be related somewhat to rutting in these sections (see Table 7-2). The coefficient of determination (r^2) for the most recent rutting measurements

vs. asphalt content is 0.58. (The correlation of rutting to asphalt content after four years of service was 0.51.) Correlation of rutting with voids content (at construction) for the most recent data set yields an r^2 =0.60; previously, that value was 0.54. As noted before, the correlation with voids indicates that higher voids content is associated with less rutting. This does not make intuitive sense because the range of voids was 6.1 to 10.8% at construction. However, the correlation coefficient for asphalt content:voids is 0.48 in an inverse relationship, and that may explain the apparent correlation between rutting and voids. Nevertheless, none of these correlations is particularly strong and the data merits closer observation.

Plots in Figure 7-1 show that rutting has increased rather steadily for sections containing Cenex asphalt. Sections 5 and 6, with fly ash and with no additive, had apparently leveled out in rutting rate until the unusually hot summer of 1988. Between February and September of that year, both showed significant rutting increases. The section with Acra has shown steadily increasing rut depths (it has the highest AC content of all the sections). Still increasing in rut depths, but at a slower rate, is that section containing lime. There is a general trend toward increased rutting with increased asphalt content here. However, if that were the only contributing factor in an otherwise controlled situation, one might have expected the Acra section, with its high asphalt content plus the contribution of the light

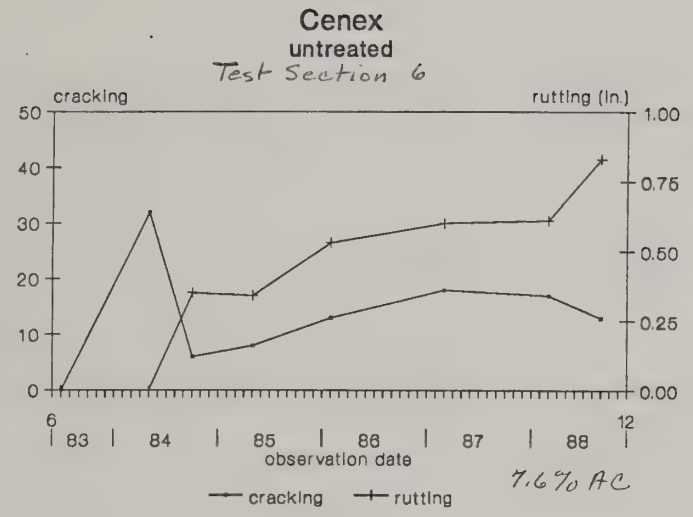
material in the antistripping agent, to show even more serious rutting than it has shown.

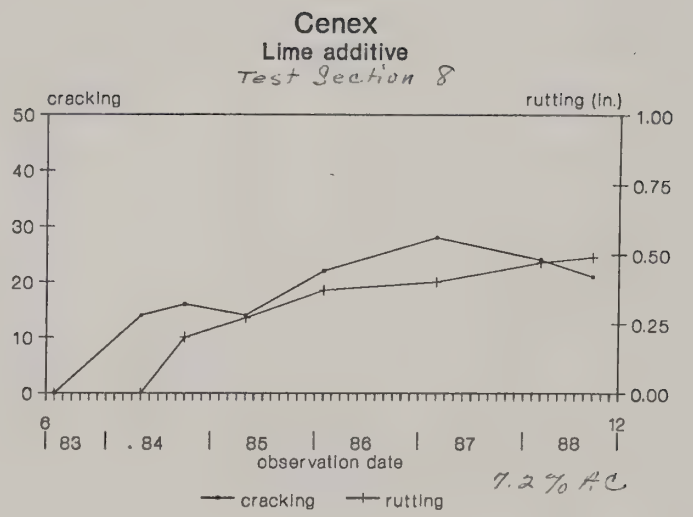
Conoco sections (Figure 7-2) with Acra and with lime had apparently leveled off in rutting rate; the Acra section did increase rut depth somewhat during the summer of '88. The other two Conoco/120-150 sections apparently continue to rut. Again, there is a trend toward increased rutting with higher asphalt content but the Conoco/untreated section is somewhat out of line.

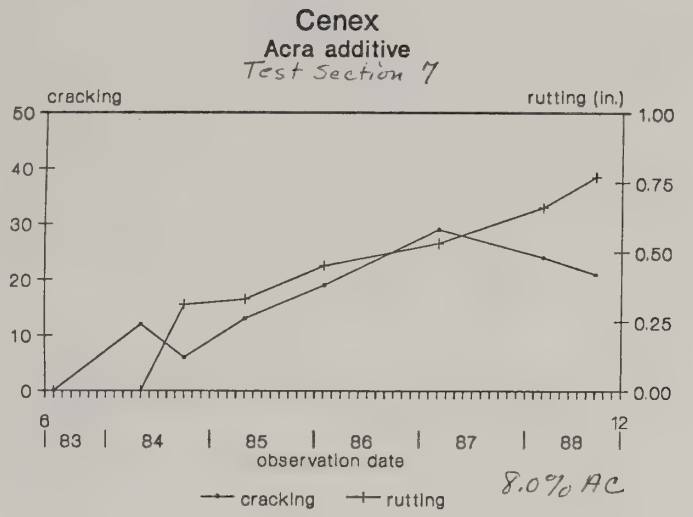
Any association of rutting with asphalt content in the Exxon sections (Figure 7-3) is tenuous except for the Acra section. In general, the Exxon sections are stable or have slowly increasing rutting rates.

The Simmons sections (Figure 7-4) all have well below 0.5 inch rut depths and, again, the association with asphalt content is not direct. Rutting has been increasing in the lime- and Acra-containing sections and has apparently stabilized in the fly ash section. The untreated section showed no increase in rutting during the heat of the summer of '88.

The Test Section containing carbon black with Conoco/200-300 asphalt (Figure 7-5) continues to rut at a rather slow rate, having reached about 0.3 inch. This additive apparently contributes substantially to the stability of a very soft asphalt. Note that the section is still in very good condition with regard to cracking. The harder asphalt (Conoco/85-100) has held relatively steady in terms of rutting after an initial measurement of about 0.25 inch. However, other sections


Cenex
untreated
Test Section 6
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
7.6% AC


Cenex
Lime additive
Test Section 8
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
7.2% AC


Cenex
Acra additive
Test Section 7
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
8.0% AC

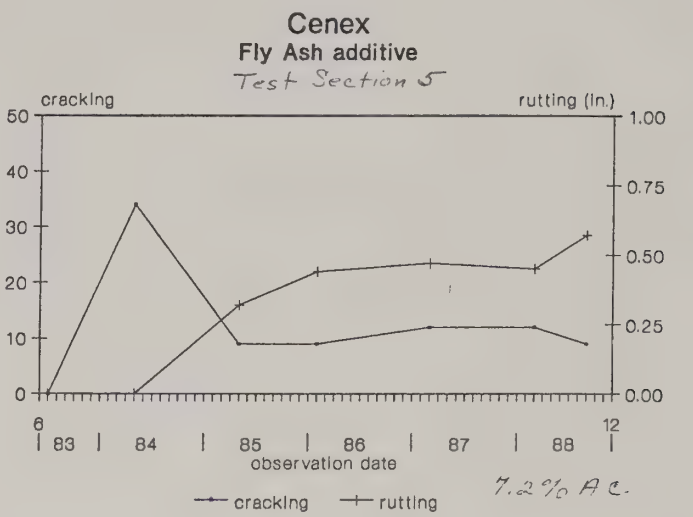
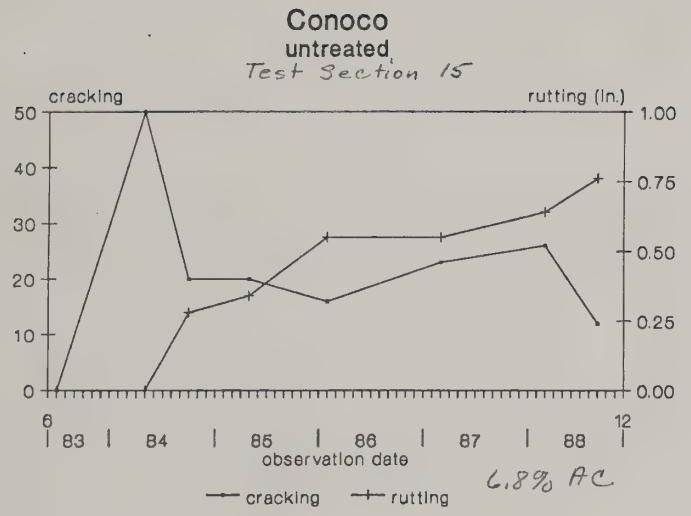
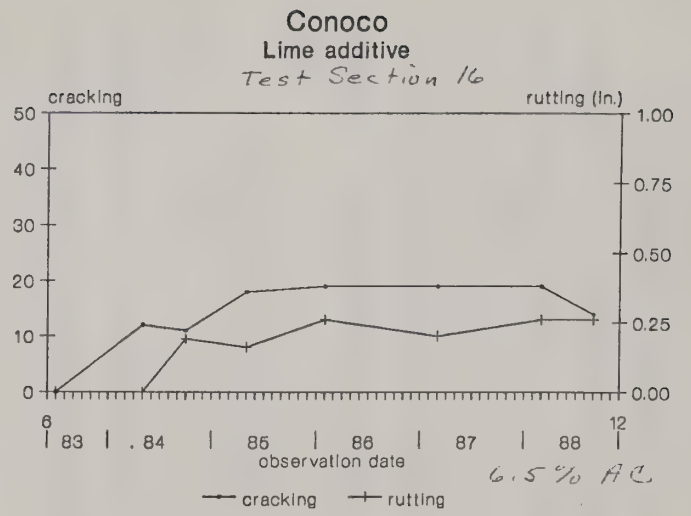
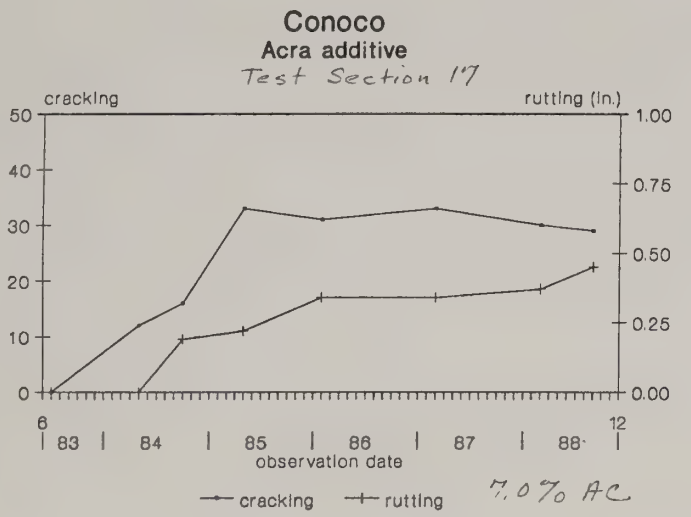
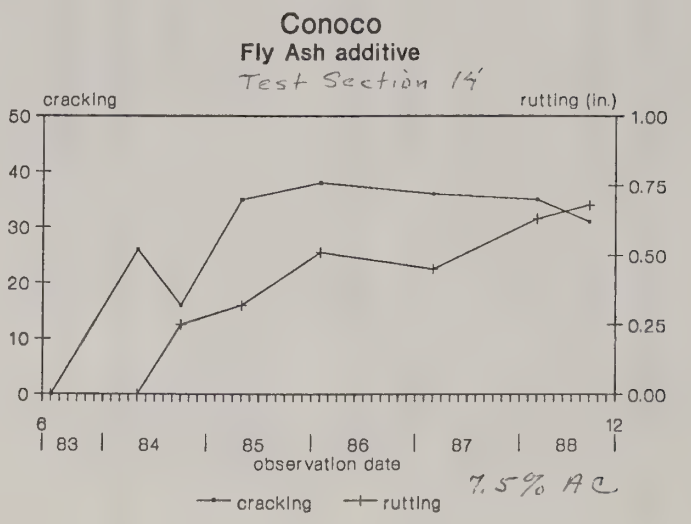

Cenex
Fly Ash additive
Test Section 5
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
7.2% AC.

FIGURE 7-1


Conoco
untreated
Test Section 15
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
6.8% AC


Conoco
Lime additive
Test Section 16
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
6.5% AC


Conoco
Acra additive
Test Section 17
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
7.0% AC


Conoco
Fly Ash additive
Test Section 14
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
7.5% AC

96

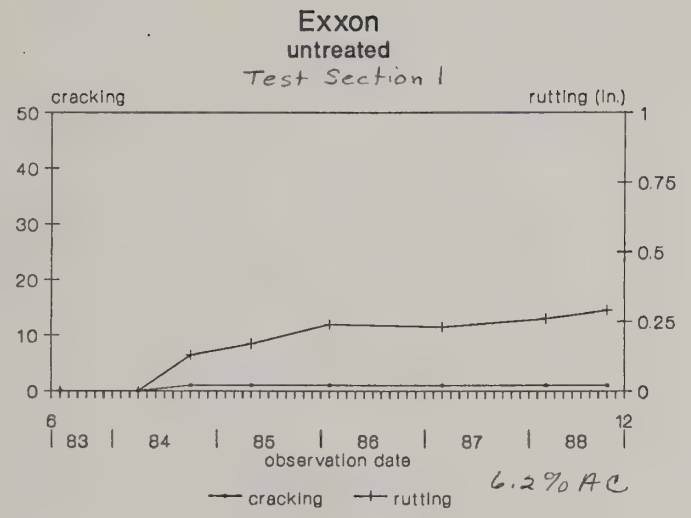
Fig 7-2

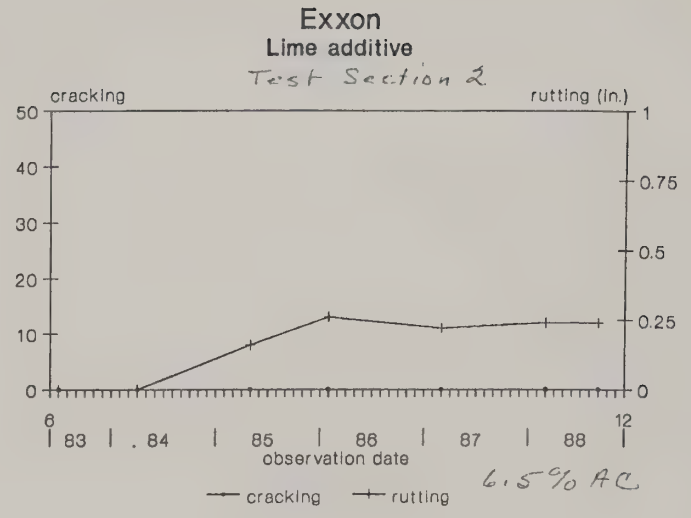
7-2

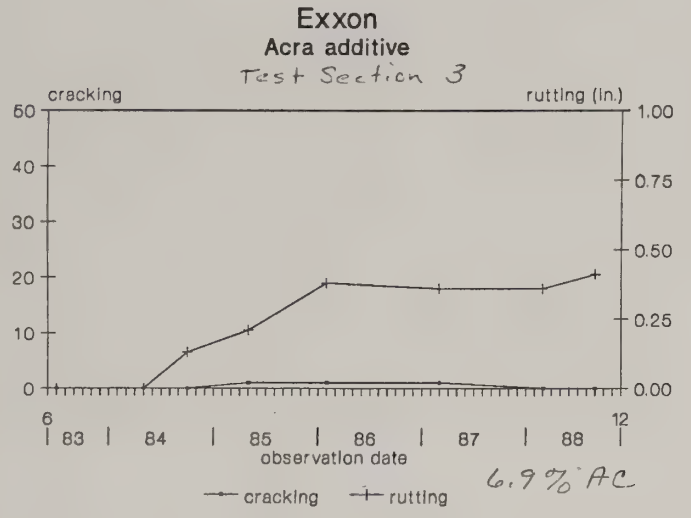
containing 120-150 grade asphalt have achieved equal or better rutting resistance. (See Table 7-1.)

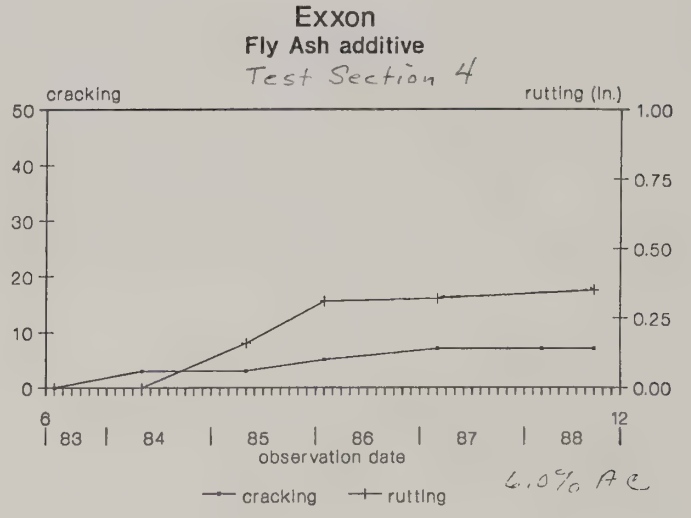
The blend of Simmons and Conoco, which was designed to be resistant to transverse cracking, has shown no sign of stabilizing in terms of rutting. This section was constructed with a 75:25 blend of Conoco/200-300 with Simmons/120-150 so the softness of the asphalt may be contributing to the rutting problem. The asphalt content is apparently not particularly high.

Figures 7-6 and 7-7 summarize the rutting data discussed above. Rutting in the Test Sections should continue to be monitored not only because of the research value but also because of the safety aspects associated with excessive rutting.


Exxon
untreated
Test Section 1
cracking
rutting (in.)
50
40
30
20
10
0
1
0.75
0.5
0.25
0
6
83
84
85
86
87
88
12
observation date
cracking
rutting
6.2% AC

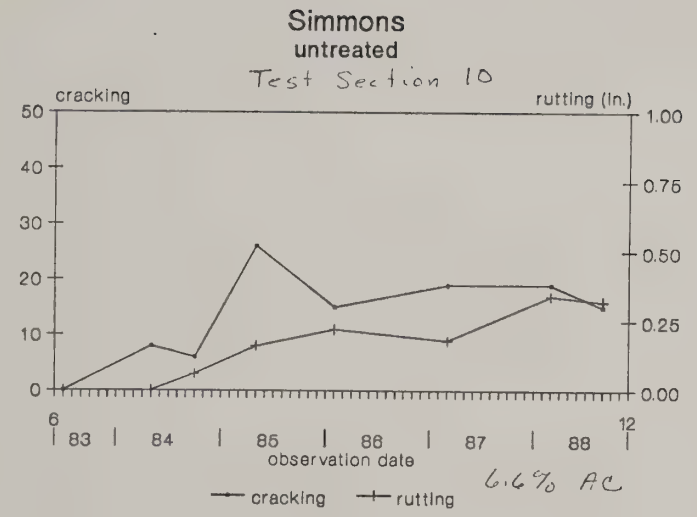

Exxon
Lime additive
Test Section 2
cracking
rutting (in.)
50
40
30
20
10
0
1
0.75
0.5
0.25
0
6
83
84
85
86
87
88
12
observation date
cracking
rutting
6.5% AC

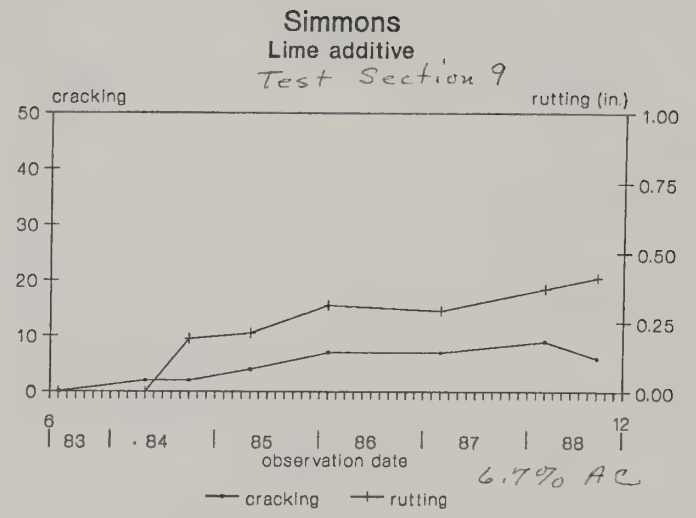

Exxon
Acra additive
Test Section 3
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
6.9% AC

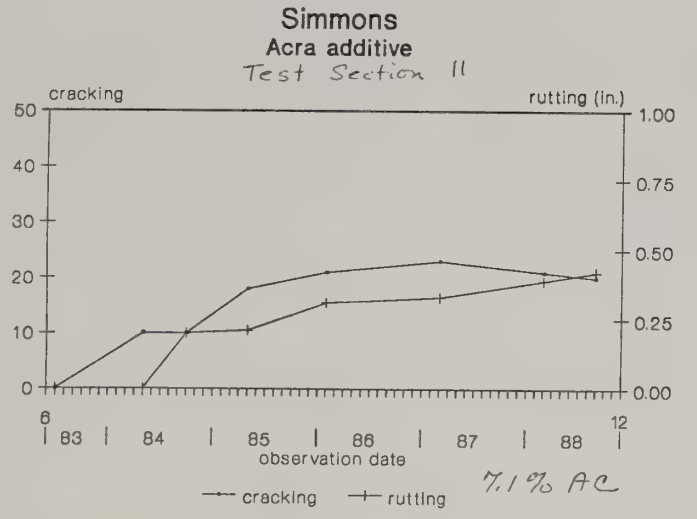

Exxon
Fly Ash additive
Test Section 4
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
6.0% AC

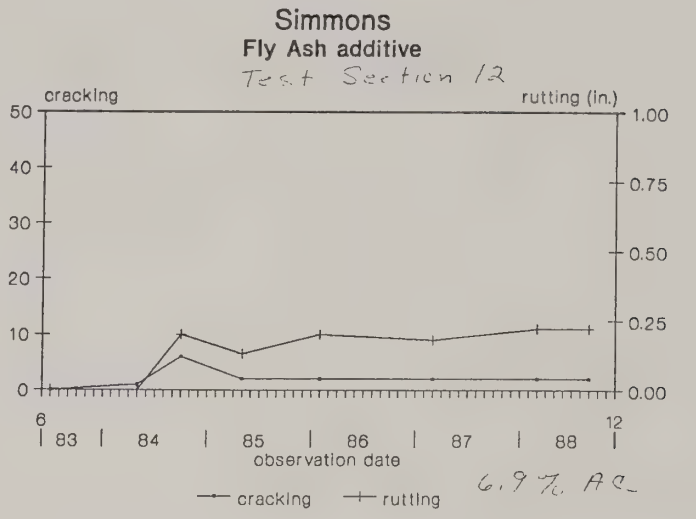
88

Fig. 7-3


Simmons
untreated
Test Section 10
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
6.6% AC

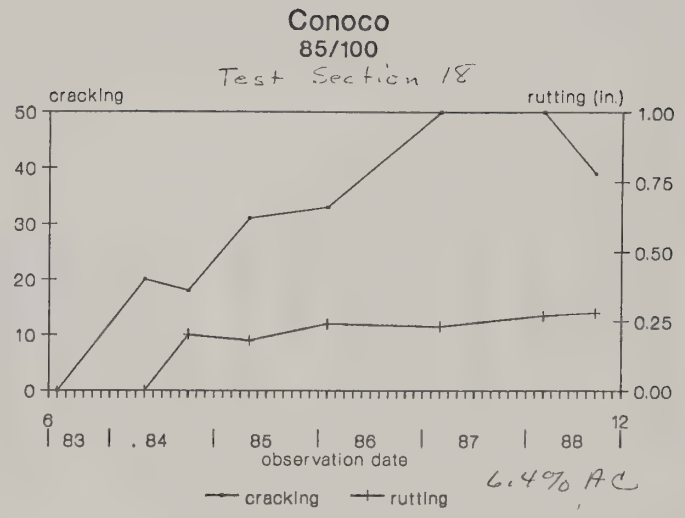

Simmons
Lime additive
Test Section 9
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
6.7% AC

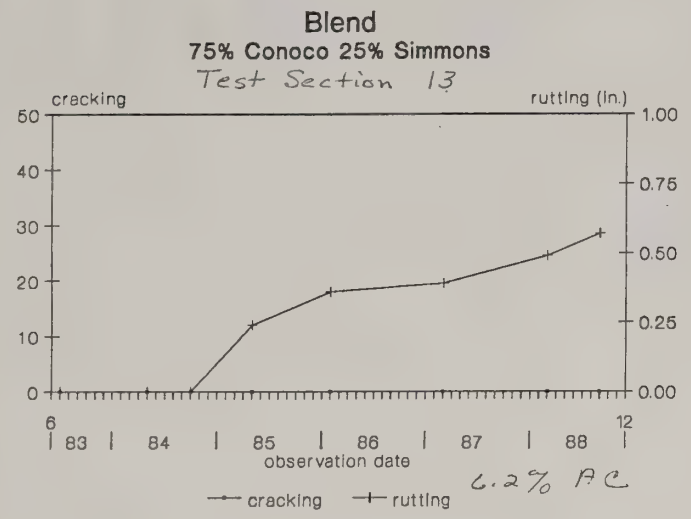

Simmons
Acra additive
Test Section 11
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
7.1% AC


Simmons
Fly Ash additive
Test Section 12
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
83
84
85
86
87
88
12
observation date
cracking
rutting
6.9% AC

94

Fig. 7-4


Conoco
85/100
Test Section 18
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
12
83
84
85
86
87
88
observation date
cracking
rutting
6.4% AC


Blend
75% Conoco 25% Simmons
Test Section 13
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
12
83
84
85
86
87
88
observation date
cracking
rutting
6.2% AC

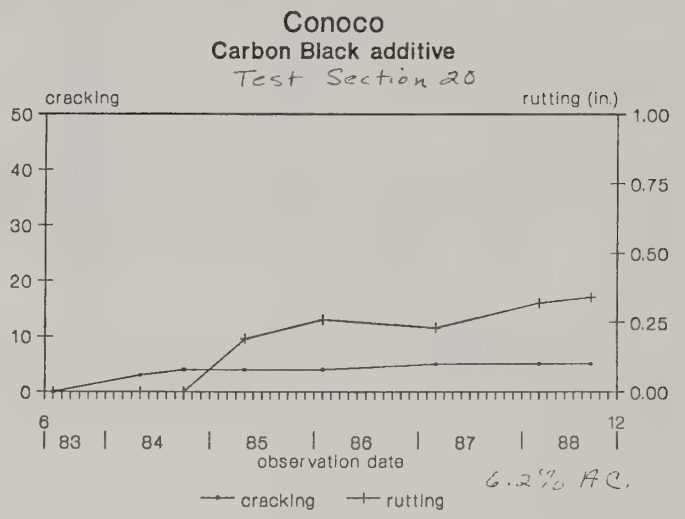

Conoco
Carbon Black additive
Test Section 20
cracking
rutting (in.)
50
40
30
20
10
0
1.00
0.75
0.50
0.25
0.00
6
12
83
84
85
86
87
88
observation date
cracking
rutting
6.2% AC.

Fig. 7-5

Table 7.2.

Data for Rut Depths, %AC and % Voids, Test Sections

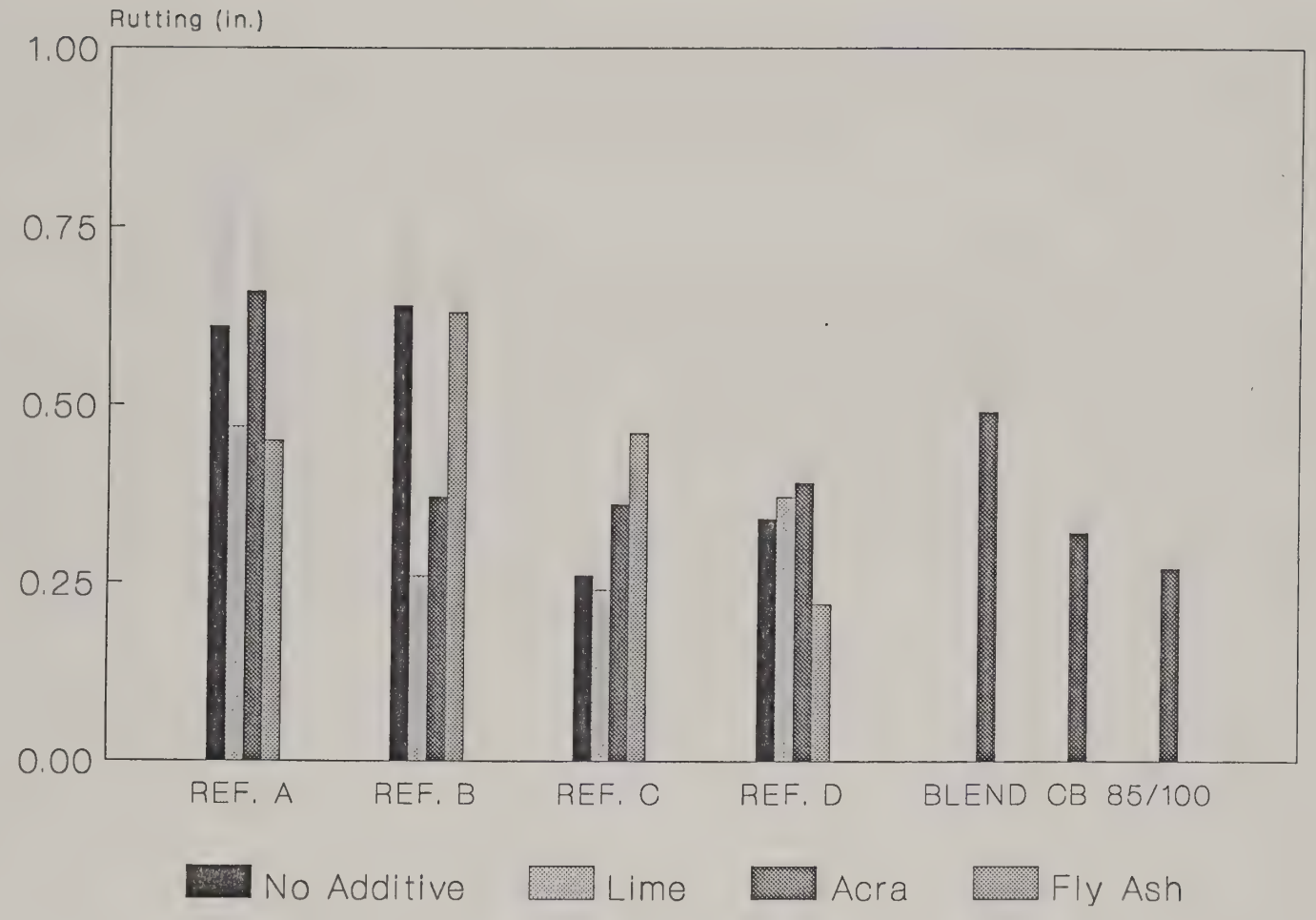
Section #	Components	Ruts, in [1]	%AC[2]	%Voids[3]
6	Cenex/	0.83	7.6	6.1
15	Connoco/	0.74	6.8	6.4
7	Cenex/Acra	0.77	8.0	5.8
14	Conoco/flyash	0.68	7.5	7.7
5	Cenex/flyash	0.57	7.2	6.2
13	Blend	0.57	6.8	8.5
8	Cenex/lime	0.49	7.2	8.5
17	Conoco/Acra	0.45	7.0	6.8
11	Simmons/Acra	0.42	7.1	8.9
3	Exxon/Acra	0.41	6.9	9.3
9	Simmons/lime	0.41	6.7	7.6
4	Exxon/flyash	0.35	6.0	8.7
20	Conoco 200+/ Carbon black	0.34	6.2	9.8
10	Simmons/	0.32	6.6	9.0
1	Exxon/	0.29	6.2	8.9
18	Conoco 8S-100	0.28	6.4	8.9
16	Conoco/lime	0.25	6.5	10.8
2	Exxon/lime	0.24	6.5	9.5
12	Simmons/flyash	0.22	6.9	7.8

[1]Average of driving lane measurements at each delineator

[2]% asphalt at construction - MDOH data

[3]% voids at construction - MDOH data

Rutting in Test Sections



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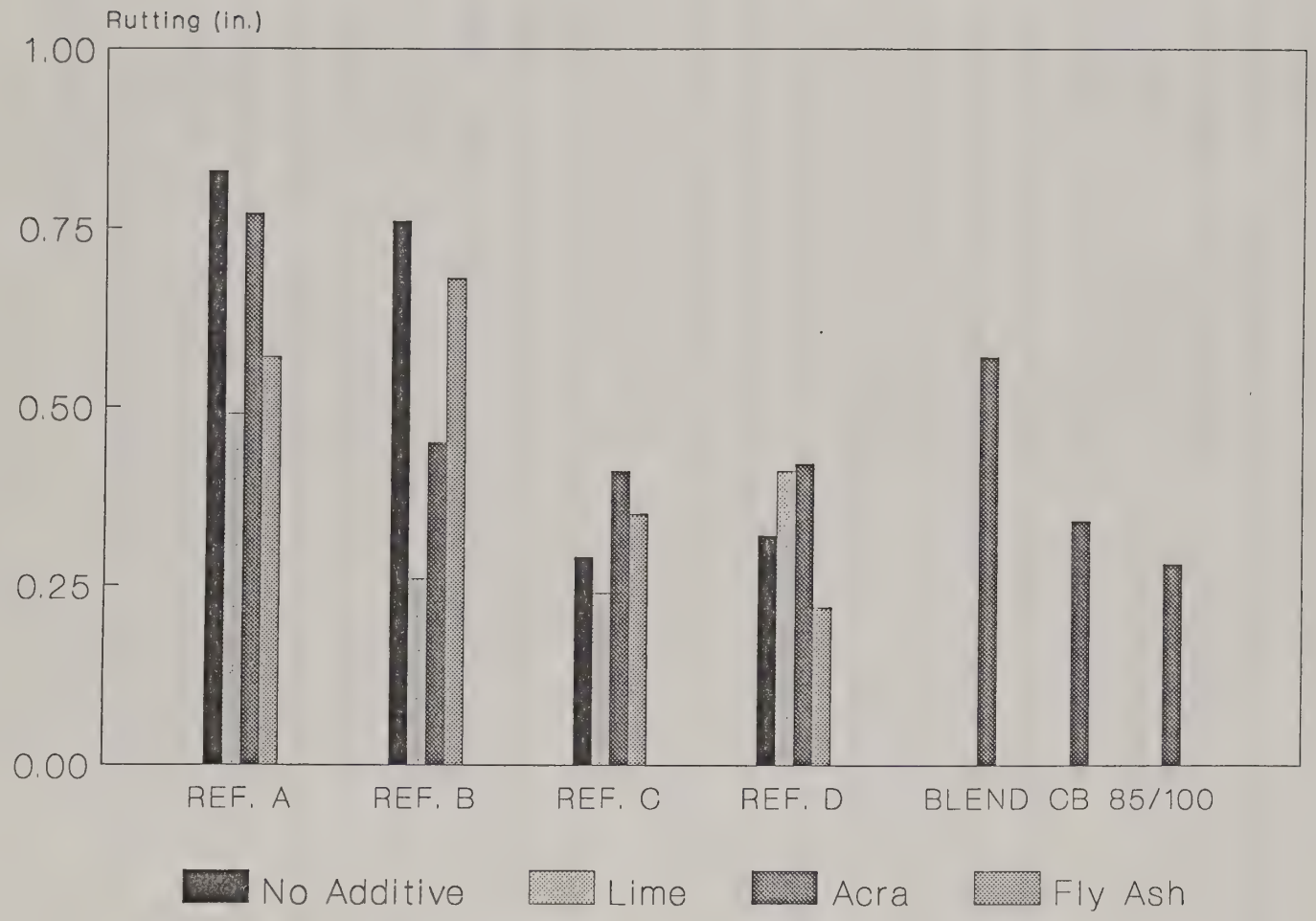
102

Fig 116

Rutting in Test Sections



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103

Fig 7-7

Cracking

The Test Sections were originally conceived to monitor the relationship between transverse cracking and HP-GPC characteristics. That aspect of the data will be discussed next, again for convenience, by refinery. In the case of transverse cracking, there is no apparent statistical relationship with any other variable. Data is in Figures 5-1 through 5-5.

[Note: In the first performance observation conducted in March, 1984, after the sections had been in place for one winter, cracks were counted in a short section and that number has been extrapolated to the full 1200 foot section. Therefore, the number of cracks at that time is not as accurate as at subsequent observations when all cracks in the full section were counted. Nevertheless, severe cracking after one winter was noted in sections 15, 5 and 6.]

Cenex test sections with no additive and with fly ash are rated "good" with respect to cracking. Both of these sections exhibited a large number of cracks after the first winter. By the fall of 1985, the number of cracks had dropped substantially and evidence of healing was visible. In both sections, the number of cracks has increased somewhat in the intervening time with another spate of healing evidenced during the summer of 1988. The sections containing lime and Acra are more seriously cracked, both being in poor condition but both also have undergone some healing.

Conoco test sections constructed with 120-150 grade AC also show a tendency to undergo healing of transverse cracks, with the most pronounced effect being in the untreated section. The number of cracks in these sections appear not to be increasing, except, perhaps in the untreated section when considered overall. However, all are in poor or bad condition. The section containing lime is the best of the four with respect to both cracking and rutting.

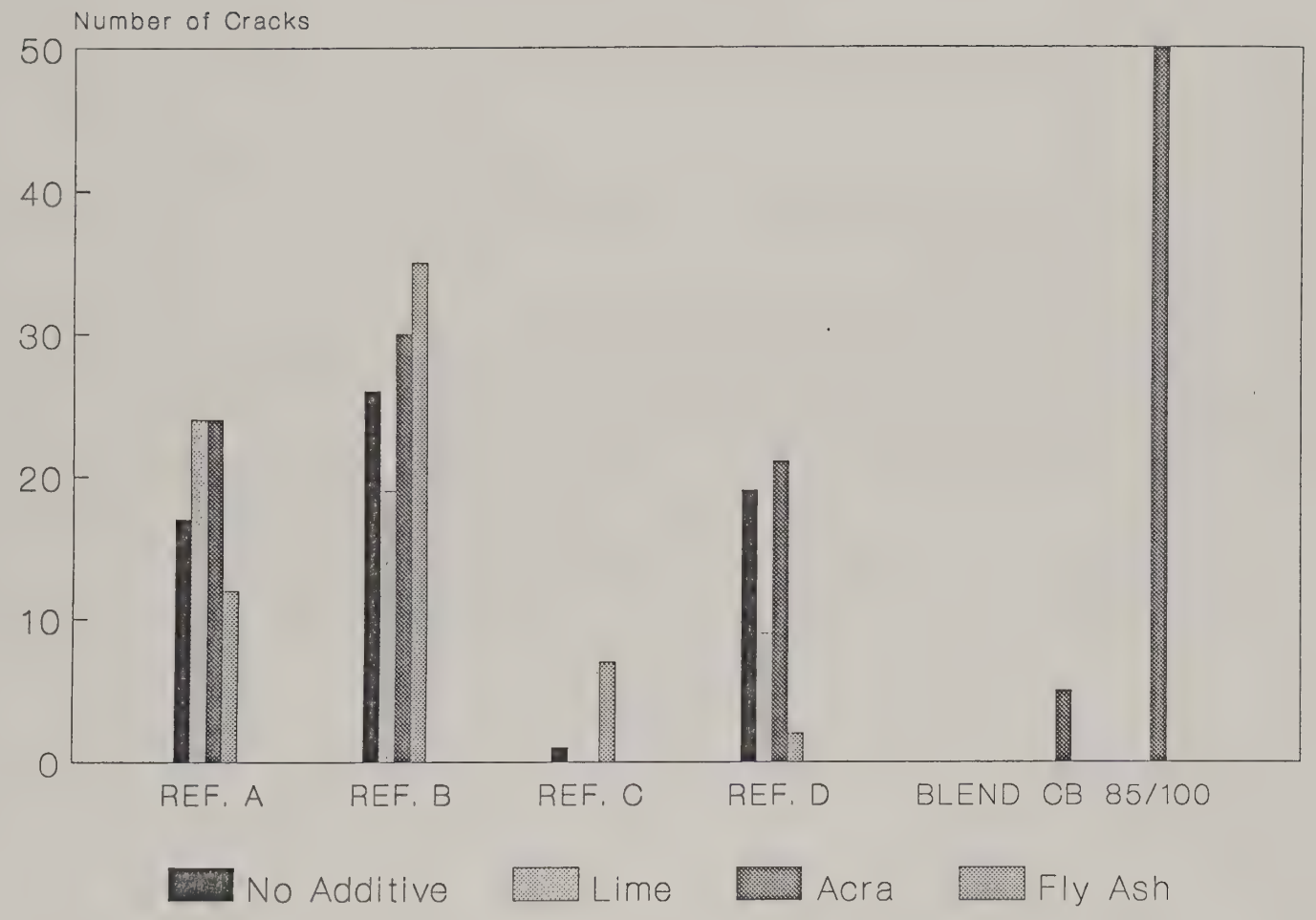
Excellent performance is still being shown by three of the four Exxon sections. These have no cracks or only one. Exxon with fly ash has apparently stabilized, the last three observations having reported seven cracks. Its performance is rated good.

The crack count in Simmons with fly ash has remained at two since May of 1985 but has increased at varying rates in the other sections. There was some evidence of healing in the other sections, as well. That with lime remains in good condition; the untreated and Acra-containing sections are in poor condition.

Rapid increases in transverse cracking have been seen in the Conoco/85-100 section although some healing was apparent during the summer of 1988. As mentioned earlier, the Carbon Black section remains in good condition and that with the blend is excellent.

Figures 7-8 and 7-9 summarize the most recent crack counts.

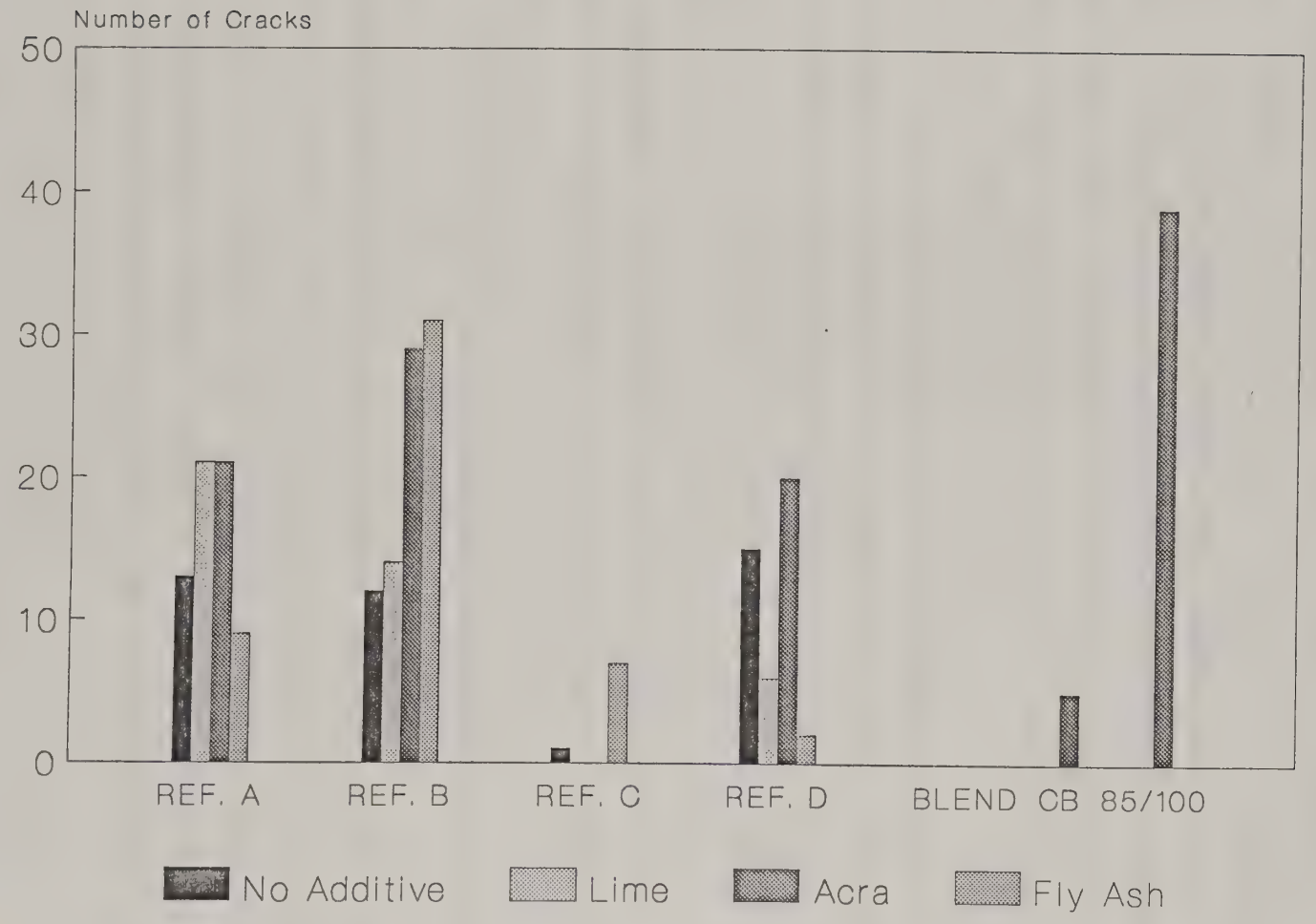
Cracking in Test Sections



2/23/88

Fig. 7-8

Cracking in Test Sections



8/30/88

Fig. 7-9

HP-GPC Characteristics.

Table 7-3 lists the percentages of LMS material found in the most recent HP-GPC analyses of cores from the Test Sections. Figures 7-10 through 7-14 display the history of this parameter from the first core samples taken after construction to the present. In general there has been some variability in the LMS content with time. In some sections there is a trend toward increasing LMS, in others little change at all and in still others a more random variation.

Cenex asphalts all showed a decrease in LMS percentage between construction and the first sampling in 1985. Thereafter, the LMS content has moved generally higher but in only one of the sections (that with no additive) is it now higher than at construction.

The Conoco 120-150 asphalt sections have the lowest LMS content of the four sources, as well as the least variability by HP-GPC, overall.

The blend of Conoco and Simmons has shown very little change overall.

Exxon asphalts have shown the widest range of LMS contents of the four sources. After an initial decrease in LMS (between construction and one year) most of the sections have undergone gradual increases. Both the lime-containing and untreated sections now have significantly higher LMS contents than at construction.

The Simmons asphalts are highest in LMS and have had moderate variability over time, most of it random. At last analysis, however, the amounts are similar to or less than at the time of construction.

As to the relationship between HP-GPC characteristics and cracking, Conoco remains an exception with high crack counts and low LMS content. With the others, the LMS percentage is not particularly relevant; however, comparison of the chromatograms is more revealing. As discussed in previous reports, the presence of unusual SMS material in Cenex skews the LMS percentage but the chromatograms show that it is in fact intermediate between Exxon and Simmons. The SMS material does perhaps, contribute to the tendency of Cenex asphalt sections to crack and to heal, but that is, of course, speculative.

Predicting Performance

A general goal of much of the work done in this laboratory has been to gain the ability to predict pavement performance, not so much to foresee cracking or rutting as to elucidate ways in which cracking and rutting can be reduced.

Broad predictive capability still exceeds our grasp. Difficulties with achieving this model are exemplified by the fact that statistical models for rutting in overlays differ from those in non-overlayed pavements. Furthermore, these models were derived for a statistical universe including only the Montana Interstate system and technically cannot be applied to other pavements in the state. In view of the problems it seems

reasonable to shift this discussion to what is known and how that knowledge can be used profitably. Various elements affecting performance will be discussed individually.

Asphalt Content

Data from the Test Sections and the model for rutting in non-overlayed pavements indicate that higher asphalt contents are related to pavement rutting. This comes as no surprise. However, it appears that the amounts of "excess" asphalt cement which tip the balance toward rutting may be small. In the projects monitored for Task 6, the average asphalt content was similar to or less than the design target, but the variability found, especially by extraction, was nearly 2% in one project.

Although it is not possible to make simple rules about asphalt content, three points may be made: 1) asphalt contents should be kept as low as possible; 2) tighter control should be maintained at construction; 3) the discrepancies between asphalt content derived from nuclear density measurements and by solvent extraction should be clarified. (For example, is mix segregation a factor, etc?)

Marshall Stability & Flow

As mentioned under Task 6, the stabilities achieved in the pavements are generally higher than those obtained by field Marshall testing. Furthermore, the pavement values are widely variable in a single project and show no particular pattern.

This apparently random variation may preclude detection of any association with pavement performance.

Voids

Voids content is perceived to be very important to pavement performance, indeed, this variable is found in the model for non-overlay pavement rutting. Voids content does not appear to be a factor in the Test Sections, however, as discussed earlier. In the heavier sampling done for Task 6 it is obvious that the variability in percent voids within individual projects makes finding relationships with performance problematic. With this background, it can only be recommended that efforts be made to control voids content at the same time that it is recognized that voids content, even in an apparently well-constructed mat, may vary widely.

Aggregate Gradation

Gradation variables have entered both rutting as well as cracking models. Unfortunately, the statistical process does not define limits to the amounts of aggregate of a certain sieve size. Rather, there is an indication that more (or less) of a given size is associated with rutting. The range of choices is defined by the data on which the model was based. It should be remembered that most of the gradations fell within or close to today's anti-rutting specification limits.

The variability found in Task 6 may indicate that it would be very difficult to control individual sieve sizes to the extent required by the model. Moreover, association of these variables

with performance is also difficult. A case in point is the difference in performance among the Test Sections constructed with the same aggregate. It is hard to conceive that the aggregate gradation changed at certain section boundaries.

It is of interest that aggregate samples collected by MDOH personnel for these Task 6 projects were virtually all within specification limits, but the broader range of samples collected at the paving site were not so well arrayed; some were not within "spec." This may be regarded as evidence for segregation. However, no data is available to show whether there are detrimental effects of segregation that shows no pattern in the pavement. Additionally, the source of this phenomenon is not obvious.

Aggregate fracture is apparently much simpler, i.e., the more aggregate particles with fractured faces, the better.

Overlays

The performance of an overlay depends not only on its own characteristics but also on the nature of the original pavement. This was made particularly obvious in efforts to obtain statistical models for all Interstate pavements. Models were not viable until overlays were separated from pavements which had not received an overlay.

Although quantitative data is available for only one case, it is obvious that cracking in the lower lifts quickly reflects into the overlay. Because so little data is available for the extent of rutting and cracking in original pavements, it is

virtually impossible to judge the performance of overlays except in the rare circumstances in which the overlays perform very well. Reports from other agencies (Task 8) are not very encouraging with regard to retarding reflection cracking with a possible exception in the use of fibers in the overlay mix.

There is some evidence that open graded friction courses (OGFC) exhibit considerable strength. However, OGFC's are not easily defined in terms common to dense graded mixes and so no data has been gathered on these layers. Our observations are that most OGFC's appeared to be performing well, although little long-term data is available since most of them were young at the time of sampling.

Asphalt Cement Variables

Viscosity and penetration values are found in models for rutting or cracking. These are values for asphalts recovered from roadway cores. At present, MDOH apparently does not collect data which might be indicative of aged consistency variables, except for penetration at 77° of TFOT residua.

Penetration grade effects are not easily interpretable because the use of different grades has varied with time. Although it was only used 20 to 30 years ago, 150-200 grade asphalts have performed well in the examples seen here (the Montana model, Gallatin Gateway-South, and the Phillips sections mentioned earlier). These sections have shown very little rutting and cracking. The best evidence for the effect of penetration grade is probably in the Test Sections. In the 20

sections paired with 120-150 asphalt cements, differences in performance are marked; some have undergone less rutting than the 85-100 section (which is also seriously cracked). Additive, asphalt content and asphalt source affect rutting more than penetration grade.

Asphalt characteristics by HP-GPC did not appear in rutting or cracking models, as discussed earlier. This could mean that the HP-GPC model is invalid, of course. It could also mean that the relationship is complex and the data set does not have the necessary information to overcome that complexity. It is known that Conoco asphalts since the mid-1970's have been exceptions to the model. Furthermore, the Test Sections indicate that additives apparently perturb the performance of asphalt in different ways, depending on their internal chemistries. Like so many other tests, HP-GPC is not a panacea.

The most simple conclusion which may be drawn is that all asphalts are not created equal. Only when ways are found of taking advantage of the strengths and avoiding the weaknesses will progress toward improved pavement quality be made. For example, there is evidence that higher LMS asphalts (such as from the Great Falls Refinery) can give adequate performance with regard to cracking and still not be subject to rutting at penetrations above 120, given due care to other variables such as asphalt content, additive choice and aggregate fracture. For example, the best Simmons test section is that with 120-150 asphalt cement and fly ash.

True LMS content (i.e., not skewed by unusual amounts of small material) of between 18 and 20% after construction still appears to give a better chance of limiting transverse cracking, although this is not fool-proof and the relative number of good and excellent performances on the interstates is lower than expected.

It must be accepted that Conoco tends to crack very early. The evidence of the Test Sections suggests that the advantage to be gained in terms of rutting by use of 85-100 asphalt is not very strong and may be outweighed by the severity of cracking. In fact, the 120-150 Conoco section with lime outperforms the 85-100 sections on both counts. Furthermore, the 200-300 Conoco with carbon black has rut depths only slightly greater than the 85-100 and has only 5 cracks -- only 4 other sections have fewer cracks. In other words, successful use of this product requires particular attention to asphalt content and judicious selection of additive as well as grade. The success of the blend with Simmons indicates that it may be a good candidate for further trials of this sort. Consideration should be given to a trial of Conoco asphalt with a fiber or polymer additive.

There are some pavements containing Cenex asphalts without the unusual SMS material that have performed well. This performance is not matched in the Test Sections. Like Conoco, successful use of the present product requires careful control of asphalt content and selection of additives. There is no data

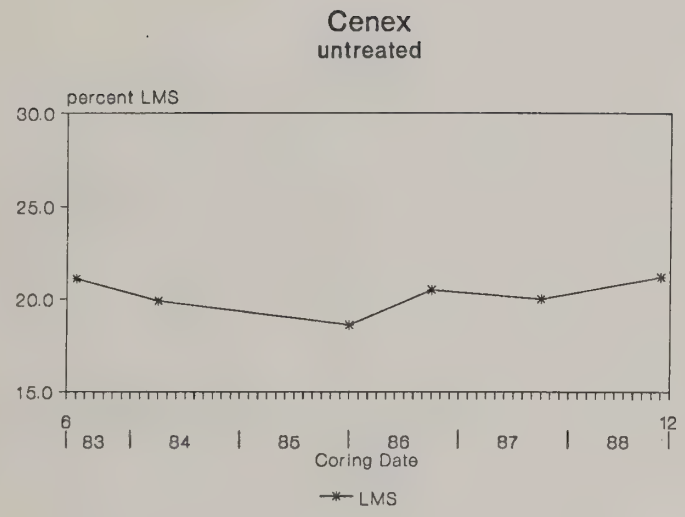
available on the effect of penetration grade with the present product.

Very old Exxon pavements and the Test Sections containing that product are performing very well with regard to cracking. There are no other pavements less than 10 years of age to give some continuity to the performance record. Those pavements over 10 years old have given less outstanding performance. Recently, there has been a change in the HP-GPC character of Exxon asphalt and there is as yet no performance information on the new product or on 85-100 grades. Since the change has involved an increase in LMS, Exxon also may now be a candidate for blending. As with other asphalts, care must be exercised in control of asphalt content and additive selection. Interestingly, fly ash is contained in the one Exxon text section that has undergone cracking as well as in the better-performing sections from the rutting/cracking study of Interstate pavements.

Table 7-4

Percent LMS in Test Sections

Sec. No.	Components	%LMS
1	Exxon/	21.7
2	Exxon/Lime	22.1
3	Exxon/Acra	21.2
4	Exxon/Fly Ash	21.9
5	Cenex/Fly Ash	20.5
6	Cenex/	20.0
7	Cenex/Acra	20.2
8	Cenex/Lime	22.7
9	Simmons/Lime	24.8
10	Simmons/	24.1
11	Simmons/Acra	24.9
12	Simmons/Fly Ash	25.4
13	Connoco/Simmons	20.0
14	Conoco/Fly Ash	17.5
15	Conoco/	16.7
16	Conoco/Acra	17.0
17	Conoco/Acra	17.0
18	Conoco/85-100	18.4
19	Conoco/ChemCrete	21.7
20	Conoco/Carbon Black	18.0


Cenex
untreated
percent LMS
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15.0
6
12
83
84
85
86
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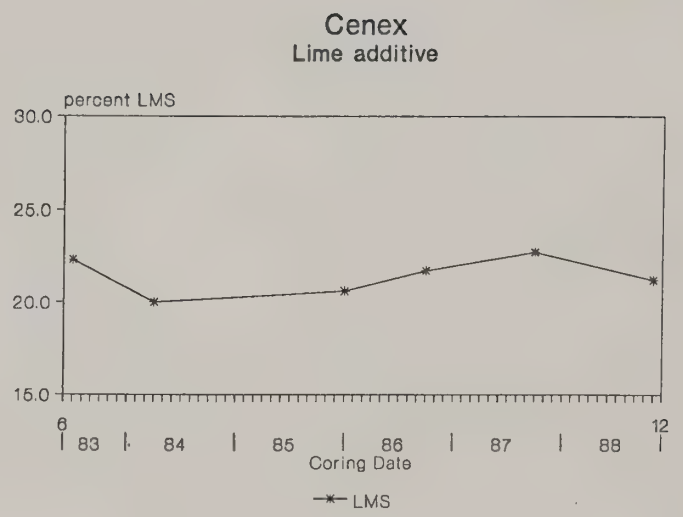
88
Coring Date
LMS


Cenex
Lime additive
percent LMS
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25.0
20.0
15.0
6
12
83
84
85
86
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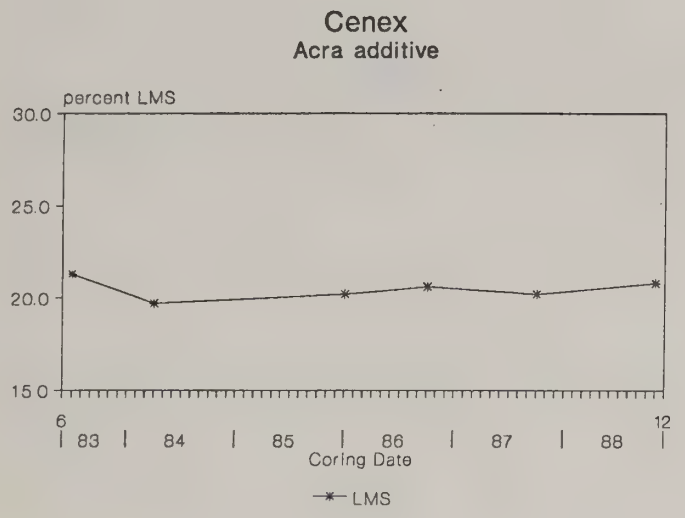
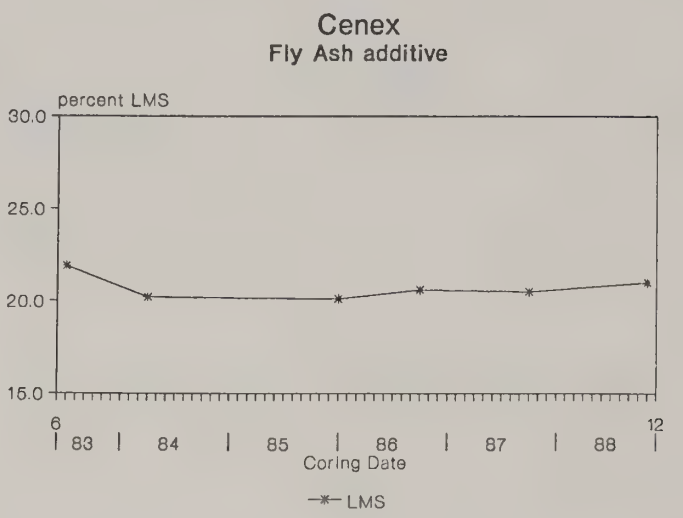
88
Coring Date
LMS


Cenex
Acra additive
percent LMS
30.0
25.0
20.0
15.0
6
12
83
84
85
86
87
88
Coring Date
LMS


Cenex
Fly Ash additive
percent LMS
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25.0
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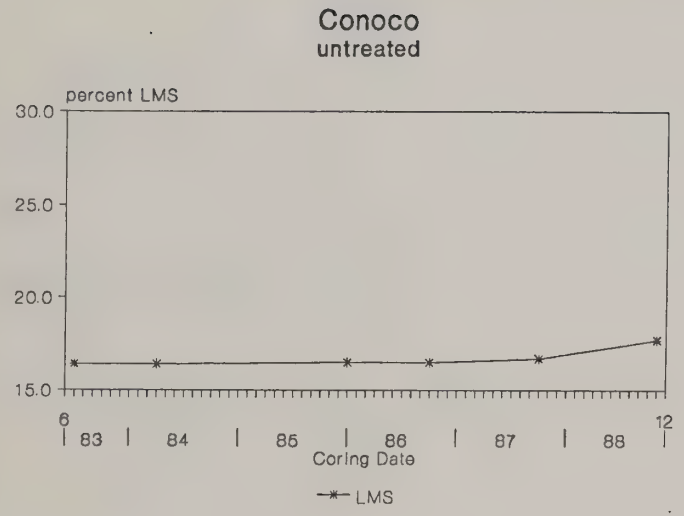
Coring Date
LMS

Fig. 4-10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untreated
percent LMS
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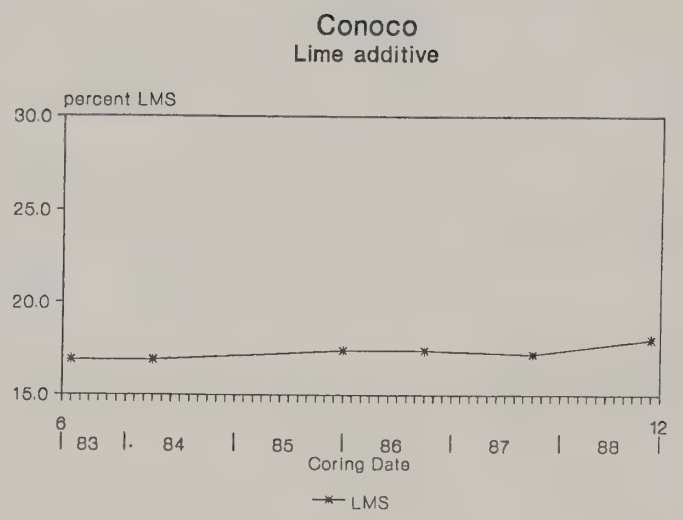
Coring Date
LMS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Lime additive
percent LMS
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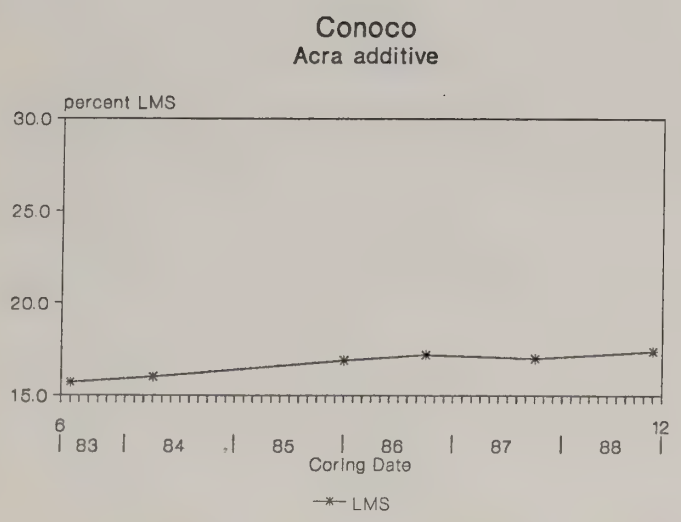
Coring Date
LMS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Acra additive
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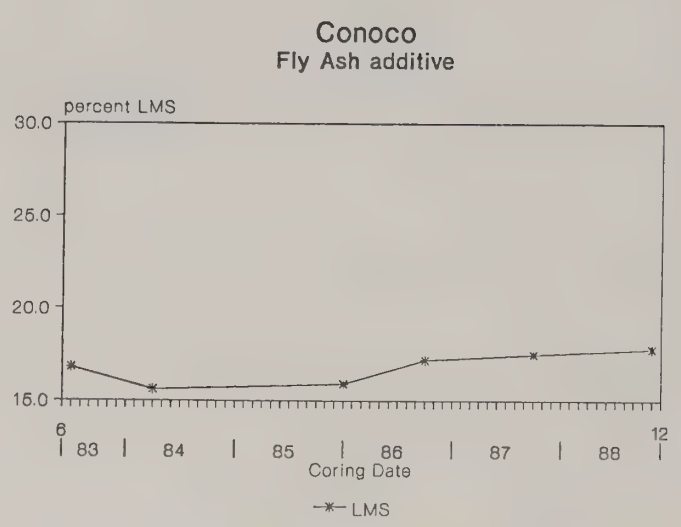
Coring Date
LMS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Fly Ash additive
percent LMS
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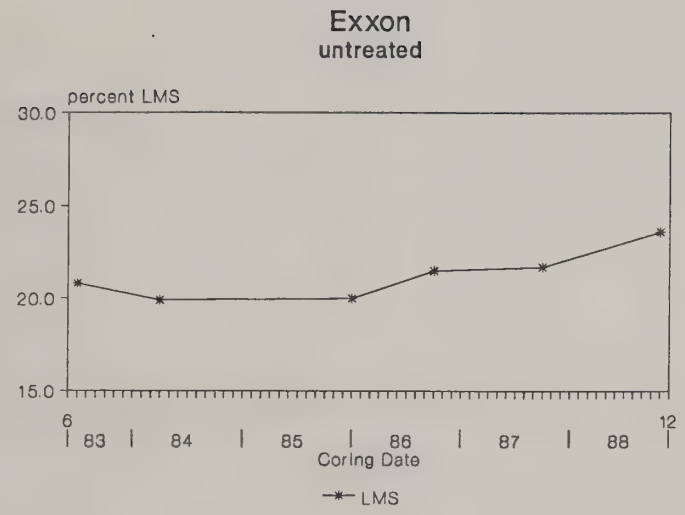
Coring Date
LMS

Fig 7-11


Exxon
untreated
percent LMS
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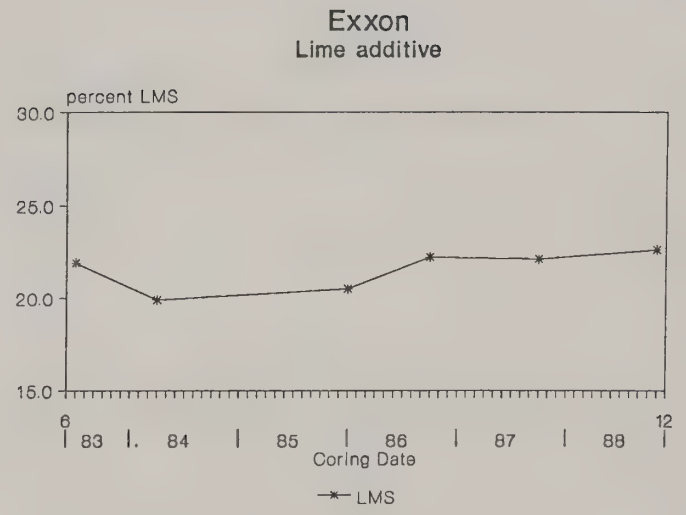
Coring Date
LMS


Exxon
Lime additive
percent LMS
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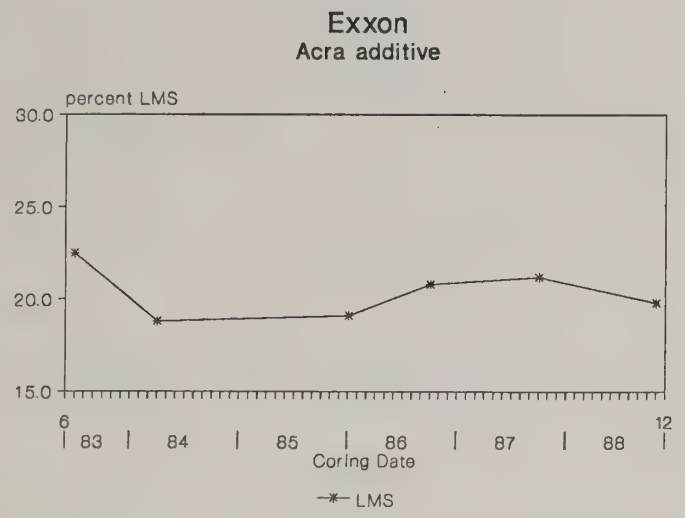
Coring Date
LMS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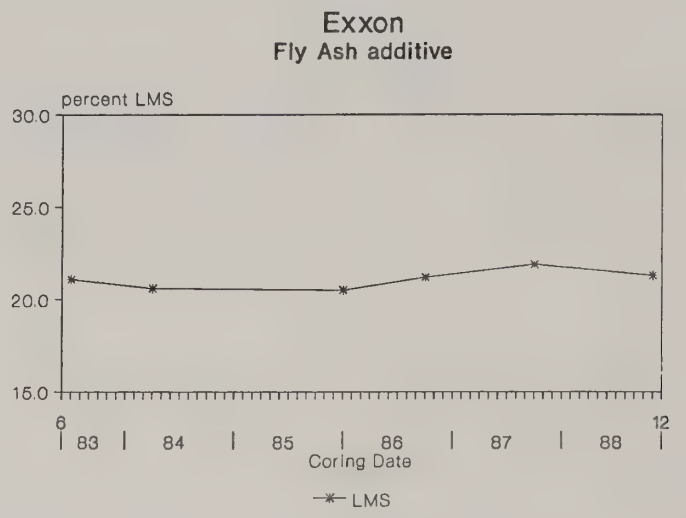
Coring Date
LMS


Exxon
Fly Ash additive
percent LMS
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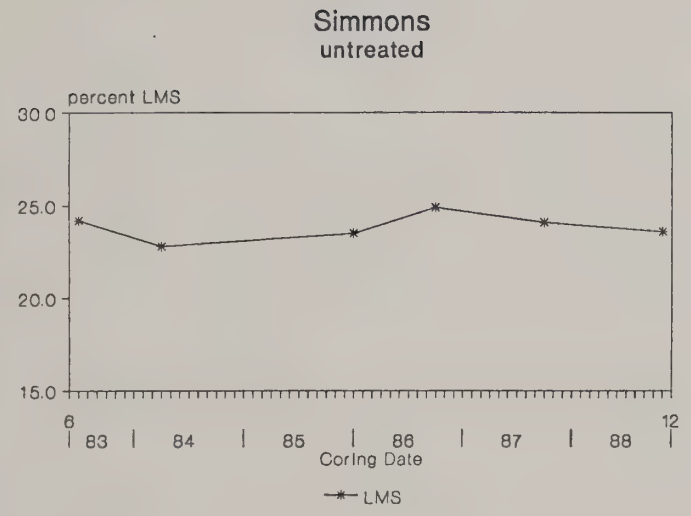
Coring Date
LMS

Fig 7-12


Simmons
untreated
percent LMS
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25.0
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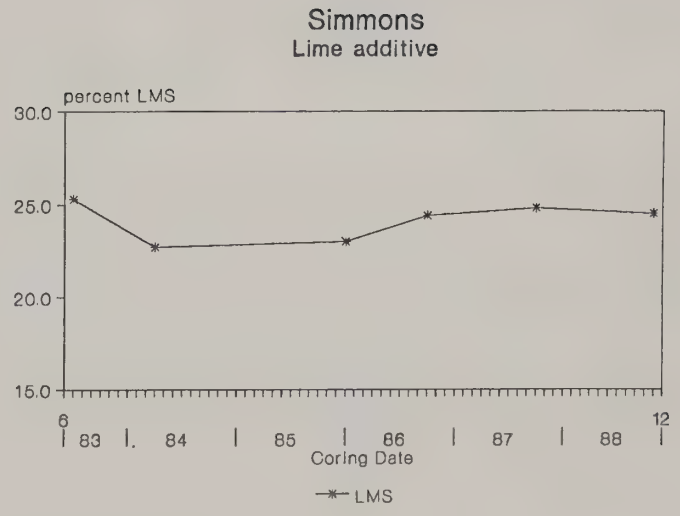
Coring Date
LMS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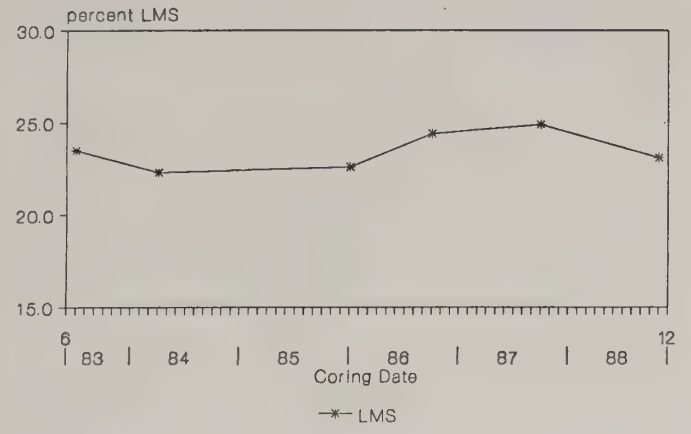
Coring Date
LMS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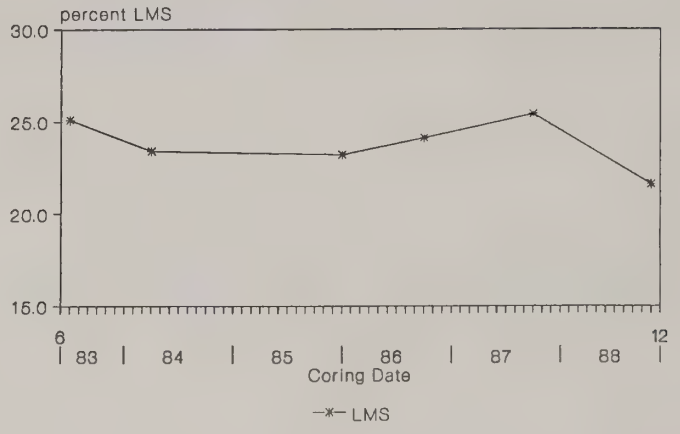
Coring Date
LMS


Simmons
Fly Ash additive
percent LMS
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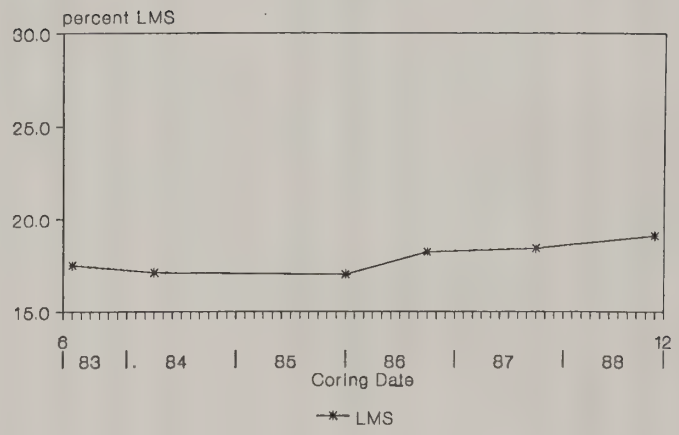
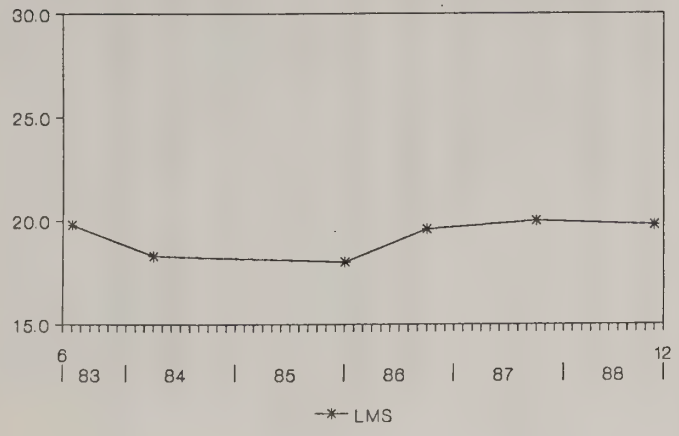
Coring Date
LMS

Fig 7-13

Conoco
85/100



Blend
75% Conoco 25% Simmons



Conoco
Carbon Black additive

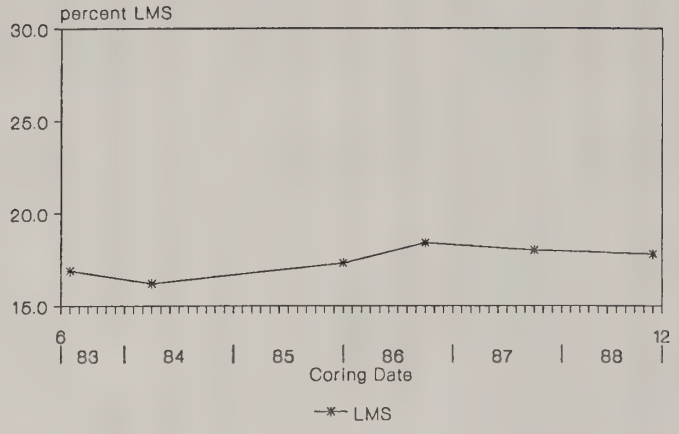


Fig 7-14

Task 8. New Advances in Asphalt Modifications

Asphalt additives and modifiers are receiving increased attention as highway agencies struggle to construct pavements that will perform well under arduous conditions.

Thirty-six state and provincial transportation agencies were surveyed in 1988 regarding their research into the use of such modifiers and additives. Of the thirty agencies responding, a few had conducted no related research. However, the others supplied information and reports on a wide range of materials.

That information has been distilled into the accompanying table (Table 8-1) the features of which will be discussed later.

Some overall observations are in order at this point. Some additives have gone through a flurry of activity but are now quiescent. Sulfur, for example, was tested by nine of the responding state agencies. Some were not disappointed by the performance of the pavements. However, the relative cost of sulfur no longer drives its use. There is concern about the environmental and health aspects of sulfur, but the agencies were able to keep emissions to a minimum in most cases.

Chemcrete, which is no longer being produced in the U.S., was also widely tested. Most agencies reported that performance was, at best, no better than controls and that cracking was the most significant form of distress. However, Montana's test section shows little cracking, although it did rut, and New Jersey finds it to be among the better performers in one of its test series.

Several agencies have used fiber additives with mixed results. These materials are expected to reduce rutting and reflective cracking. Ontario, Ohio and Pennsylvania have seen some benefit; Illinois reported good results with patching mixes containing fibers. Users must use adequate mixing time with these additives and a soap must be added to water for the roller to avoid pick-up.

There is some confusion over semantics with regard to the terms "latex," "polymer" and "rubber." For purposes of this paper "latex" includes styrene-butadiene (SB or SBR), neoprene, and other materials which are presumed to be used as liquid "latexes." "Polymer" covers polyethylene, ethylene vinylacetate, and styrene-butadiene-styrene, some of which are added as solids to the mix. The term "rubber" is restricted to reclaimed rubber, ground rubber tires, in various formulations. Admittedly, the distinctions are somewhat blurred, so all three sections of the Table should be scanned if a product is not found where one might expect it to be found.

With latexes, mixing and placement temperatures must often be higher than usual so that the mix may be worked smoothly. In general, agencies report that latex-modified materials are performing at least as well as controls. These have been used in chip seals with better chip retention in early stages.

Other polymers have been used by five agencies. Some have found reduced rutting and shoving, but not reduced reflection

cracking in polymer-modified overlays. Louisiana has been particularly happy with its polymer modification efforts.

Rubber has been used in a variety of forms, also to mixed reviews, particularly with regard to the deicing capabilities of one product.

The "Miscellaneous" category includes sulfur and Chemcrete, mentioned earlier, as well as other materials. For example, a product called "Verglimit" which is used to retard ice formation, particularly on bridge decks, has been tested by several agencies. Ohio has the most experience with this material. Carbon black has met with success in some trials.

Reports have been referenced in each case in which one is available. These reports generally have laboratory and field testing information as well as discussion of construction experience. In a few instances, "special provision" requirements and/or specifications have been made available.

Specifications and compliance testing for these new products apparently remain a problem for some users. Design criteria are often keyed to the Marshall method. Still, some expressed concern that these standard methods are inadequate for products with such vastly different properties. Nevertheless, agencies appear willing to try new products not only in the expectation of gaining knowledge, but also in the hope of achieving significant improvement in their pavements--all with a healthy dose of skepticism.

The Table

Table 8-1 is divided into five sections, "Fibers," "Latex," "Polymers," "Rubber," and "Miscellaneous," using definitions described above.

Performance is rated (when available from agency) according to the following grade system:

A - Excellent

B - Better than control

C - Equal to control

D - Worse than control

E - Failure

Comments on performance, construction, etc., are either direct quotes from the agency or summarized from its report.

Reports are referenced numerically in the table and listed at the end of the table.

Abbreviations used are as follows:

AB - acrylonitrile-butadiene

EVA - ethylene vinylacetate

OGFC - open-graded friction course

PMS - plant mix seal

SAMI - stress-absorbing membrane interlayer

SB - styrene-butadiene - latex

SBR - styrene-butadiene - latex

SBS - styrene-butadiene-styrene - block copolymer

SEA - sulfur-extended asphalt

LATEXES

TABLE B-1

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
VT		Ultra Pave	Tests--Emergency Repair	yes	84	87	C	Test compromised by problems with Substructure	(31)
IA		Ultra Pave	Resurfacing	yes	83		C	Some difficulty with steam generated during addition of product; tearing on placement. No significant difference from control.	
MA		Ultra Pave	Test sections--High speed, high traffic.	yes	87	88	C	Crews tired because of sticky mix.	(15)
NJ	SB	Texcrete	Test Sections--For rut and crack resistance	yes	86		D	Earlier cracking than control. Compared with ChemCrete, Solar Laglugel, 3M-5590, PlusRide	(46)
NB	SB		Heavy traffic	yes	88			Mix showed less tendency to segregate; open-graded needed to be >280 degs. to prevent tearing.	
MI	SB		Overlays--some on CRC	yes	76-84			Reports contain lab and construction info as well as a special provision.	(16)(17) (18)
WA	SB		Tests in asphalt concrete.	yes	86,87		C		
MN	SB		Plant mix/seal coat	yes	88		C/F	Additional pump needed; laydown slow; plant mix same as control; seal and its control both failed.	

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
LA	SB		Slurry Seal/airport		74				
LA	SB		Dense graded plant mix	yes	82		B	Better skid resistance than conventional mix.	
LA	SB		Dense graded P.M. on orthotropic bridge deck		87				
LA	SB		Chip seals.		85			Latex may be less convenient than Styrelf--one application failed because of plugging of distributor due to incompatibility of particular emulsion and SBR.	
LA	SB		Overlay of PCC	yes	87			This test pavement included use of SAMIs and sawed-and-sealed joints. Some immediate cracking was noted at PCC joints; also some shoving over membrane.	(54)
IAN	Neoprene		Timber bridge deck					Increased deck surface life from several months to several years. Slight compaction problem due to nature of mix.	
A	Neoprene		Tests in chip seals	yes	86,87		C	Better immediate chip retention.	
N	Neoprene		Plant mix/city street	yes	86				
A		Ralumac	Emulsified Slurry Seal		82,88			Very stable, no ruts, cracks reflected but sealed in '82 pvmt. Some rutting. in '88 pvmt.	

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
UT		Ralumac	Rut filling/roadway leveling, slow stripping	yes	85		B	Rutting recurs, but effectiveness is adequate.	(28)
PA	Latex-modified cationic emul-sion.	Ralumac	As SAMI over cracked PCC	yes			C	Ralumac paving system, Type A--Construction and special provisions in report.	(13)
FL	Latex		Intersection used by many heavy trucks--caus-ing rutting, shoving, cracking.		88			Increased mix temp.; okay after 6 months	
AZ		HFE 1509	Test sections--modified emulsion cold recycle.	yes	87				
UT	Latex		Inlays in previously rutted pavement	no	86	88		Appears stable to date.	
WI	Latex		Sealcoats in heavy traffic					Being replaced with "heavy float" emulsions.	
ME	Various Latexes	Dow	Tests conducted by Dow--overlays	yes	86		C	No rutting, little cracking on project. Principal investigator--Jon Epps, Ph.D., Univ. of Nev., Reno.	(41)(42)
IL	SB	Pliopave UltraPave Rub-R-Road Dow Polysar	Sand-asphalt-bridge decks and pavement						

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
CO	SB Neoprene SB	Styrelf	Chip seals (from emul-sion), plant mix seals		60-88			Higher placement temp for PMS; "Gener-ally good performance from modified Ac's"; "plant mix seals and chip seals have greatly helped raveling"; rutting being evaluated.	
NY		Ultrapave Polysar	Tests in surface treat-ments	yes	84 85		C	Additive mixed with emulsion.	
ONT		Polysar	Open-graded friction course	yes	85		B	Soap needed on roller. Construction and lab results in report.	(8)
PA	SB Neoprene	Rub-R-Road duPont neoprene	Wearing course, seal, SAMI on severely cracked pvmt.		82		C	Precautions about mix temp and rolling noted.	(11)(12)
CA	Neoprene SB		Chip seal emulsions. Also in slurry seals and in hot mix.		87-88			Permits sweeping first day.	

POLYMERS

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCES
VT	Nat. resin/ nylon	Solar Laglugel	Wearing course		82		C	Not cost effective for general use; may enhance performance of a marginal mix.	(29)(30)
IL	Nat. resin/ nylon	Solar Laglugel						No benefit over control.	
IA	Polyethylene	Asphadur (now 3M-5990)	Overlay	yes	79	83		Cracks, but no rutting or shoving. Agent increased stability but not strength or durability.	(47)(48)
IL	Polyethylene	Asphadur	Intersection approach					Similar to control in rutting and shoving.	
IA		Ductilad	Chip seal, emulsion	yes	87	88		Excellent chip retention.	
SASK		Ductilad	Emulsion/seal coats	yes	87	88	A	Binder remained flexible after one winter.,	
IA	SBS	Styrelf	Chipseal-maintenance		86			Very good chip retention, reflected cracks sealed.	
IA	SBS	Styrelf-13	Slow or stop distortion at intersections, etc.		84			Significant reduction in distortion; did not stop crack reflection; testing, observations in report.	(50)
IL	SBS	Styrelf	Weigh station, bridge deck		86				

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
A	SBS	Styrelf	Emulsion/chip seals		82		A	On high speed/high volume roadways, no loss of aggregate or flushing up to 5 years. Repair ravelled pvmts. until scheduled overlay.	
A	SBS	Styrelf	Rumble strips				A		
A	SBS	Styrelf	Friction course	yes	84	88	A	Control section failing within months of const.; Styrelf, SBR latex, higher AC content doing well.	
A	SBS	Styrelf	two in. dense graded overlay	yes	87			Compare Styrelf, SBR latex and conventional mix.	
L		Rosphalt	Bridge waterproofing Interlayer, voidless sand mix		86			Limited success.	
R		CA(P)-1	Test sections--hot mix overlay on badly cracked distressed pavement.	yes	85			Two sections, one with lime, one without	(20)(21)
T		HL-PolyPhalt	Patching material modifier--test sections	yes			B	Spray material in pot hole and over patch. Patches more durable and stable.	
E	various	Dow	Tests conducted by Dow--overlays	yes	86		C	No rutting, little cracking on project. Principal investigator for Dow Dr. Jon Epps, Univ. Nev., Reno.	(41)(42)

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
NJ	Polyethylene EVA SBS-Thermo-plastic	Novophalt Polybilt Kraton	Tests--intersection overlays	yes	87			Adequate mix temp. required for work-ability. Testing data in report.	(44)
NJ	Polyethylene Nat. Resin/ Nylon	3M-5990 Solar Laglugel	Testing sections--full depth construction	yes	84			Polyethylene -- Earlier cracking dis-tress than control; Solar Laglugel one of better additives; compared with an SBR latex, ChemCrete, PlusRide.	(46)
IA	"Polymerized A.C."		Surfacing		86			Construction data, specifications in report.	(51)
Sask		ESSO Husky	Reduce rutting " "		88 88			Not constructed at time of survey. " " " " "	
PA	EVA EVA	Ductilad Polybilt Kraton Elvax 150W	Seal coats	yes	87	88	B	Est. modifier cost effective if material lasts 2 years longer than control.	(9)
CO	EVA		Chip seals from emulsions plant mix seals		60 to date			Needs higher placement temp for PMS; generally good performance from modified AC's; raveling reduced.	
WA	EVA		Tests in chip seals Tests in A. concrete	yes yes			C C		
CA	SBS Polyethylene							Study just beginning.	

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
ALB	Polymer modi-fied asphalts	Husky Imperial	Test sections--overlay		87			Report discusses construction, testing and cost considerations.	(24)
BC	Styrene-Malan		High float emulsions for seal coats	yes	86		B	Better chip retention.	

RUBBER

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
ALB	Granular Rubber	PlusRide	Test sections	yes	85			Deicing capabilities under light or "black" ice conditions; extra cost may be warranted on bridge decks, steep slopes, at intersections.	(22)
NJ	Granular Rubber	PlusRide	Test sections	yes				Report contains a review, as well as NJ experience.	(45)(46)
IA	Granular Rubber	PlusRide	Test sections	yes	85	88	C	In several sections, no significant deicing capability.	
MN	Granular Rubber	PlusRide	Plant mix		85	88	B	No significant deicing; less raveled cracks, possible rut resistance.	
CA	Granular Rubber	PlusRide	Increase durability in problem areas						
AZ	Granular Rubber	PlusRide	Test sections	yes	85				
OR	Granular Rubber	PlusRide	Test sections--hot mix overlay on badly cracked, distressed pavement.	yes	85				(20)(21)

AGENCY	GENERIC COMP.	BRAND	USE	CONTROLS	DATES CONST	DATES EVAL	PERFORMANCE	NOTES	REFERENCE
OR	Granular Rubber (fine)	Arm-R-Shield	Test sections--hot mix overlay on badly cracked, distressed pavement.	yes	85				(20)(21)
CA	Granular Rubber (fine)	Arm-R-Shield Overflex	Increase durability in problem areas.					"Rubber mixes appear effective." Evaluating reduced thickness of rubber mixes.	
IL	Granular Rubber	Ramflex	Overlay		68-73			No significant improvement over control.	
CT	Granular Rubber	Arizona Refining	Test overlay	yes	80	86		Less longitudinal cracking, more transverse, similar skid resistance; possible contribution of original pavement to cracking not known.	(34)
ONT	Crumb Rubber		Overlay and new construction	yes	80			"Not performing as anticipated." Construction and testing in report.	(4)
WI	Crumb Rubber		Surface courses	yes	87	88	D	Some difficulty with addn'n. of rubber. Many more reflective cracks than control.	
MI	Crumb Rubber							Unsuccessful	
CO	Crumb Rubber		Chip seals and interlayers		75-80				(19)
MAN	Crumb Rubber		Seal coat in.cutback		52		C		

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
AZ	Asphalt Rubber		chip seals SAMI to retard reflec-tive cracking OGFC on PCC Asphalt concrete		late 70's			SAMI effective in retarding reflection except for well-developed thermal cracks. OGFC on PCC "very successful." Dusty chips require precoating; may encourage stripping in poorly compacted overlays; difficult to run acceptance tests.	
NJ	Reclaimed Rubber		Crack and Joint Sealants						

FIBERS

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
Ont	Polyester	BoniFibers B	Overlay cracked, high-volume highway	yes	87	88	B	Less reflective cracking than control	(5)
OH	Polyester				83		D		
PA	Polyester	Dacron	Overlay, dense-graded	yes	76		C	Must increase asphalt content, mixing time. "Build-up" on equipment requires frequent cleaning.	(10)
PA	Polyester	BoniFibers B	Overlay on ID-2 plus PCC base.	yes	85		C	Asphalt content important; early benefit seen.	
MA	Polyester	Foss Fiber	High speed, high traffic sections.	yes	87	88	C	Soap required in roller-water; Sufficient dry-mix time needed.	(15)
OH	Polypropylene		Overlay mixes	yes	84-5			Four projects; appears to retard reflective cracking, reduce rutting and shoving. Ohio is preparing specs. for use of fibers.	
CA	Polyester Polypropylene Polypropylene	duPont BoniFibers Hercules Fiberpave 3010 Phillips Marvess Olefin	Increase durability in problem areas.					Not particularly effective " "	
OR	Polypropylene Polyester	FiberPave BoniFibers	Test sections-hot mix overlay on badly cracked, distressed pavement	yes	85			Mix includes antistripping agent (Pave Bond) Mix includes antistripping agent (Pave Bond)	(20)(21)
IL	Polyester Polyester Polypropylene	BoniFibers Petroflex FiberPave	Cold patching mixes.					Good results.	

MISCELLANEOUS

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFO MANCE	NOTES	REFER-ENCES
NJ	Natural Bitumen	Gilsonite	Maintenance of severely rutted areas					Retarded rutting distress (previous rutting in 3 mos.); some cracking after two years.	
NJ		Chemcrete	Test sections for crack and rut resistance		86			One of better performing additives. Compared with SBR latex, Solar Laglugel, Polyethylene (3M-5990) and PlusRide	(46)
IA		Chemcrete			86		F	Rapid cracking.	
IL		Chemcrete					C,D	Equal to or worse than control in three projects	
NH		Chemcrete		yes			F		
ME		Chemcrete					D	Severe cracking.	(43)
LA		Chemcrete	Roadway wearing course	yes	83	87	C	Non-uniform blending.	(52)
OH		Chemcrete			81-83		D		(3)
IL	$CaCl_2$/NaOH	Verglimit						Problems with durability.	
VY	$CaCl_2$/NaOH	Verglimit	Deicing bridge deck.	yes	87				(35)
OH	$CaCl_2$/NaOH	Verglimit	Control icing		81-87		B	Seven projects; appears useful on bridge decks in Ohio climate.	

MISCELLANEOUS

ENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
A	$CaCl_2$/NaOH	Verglimit	control icing					"Raveled early; mixed reviews (on) deicing effectiveness." Trying increased compacting effort.	
A	Carbon Black		two test sections		77,84			"Older section showing poorer performance."	
I	Carbon Black	Microfil 8	Test overlay	yes	85		D	Some dust irritation at construction; approx. 2X linear feet cracking as control in 2 yrs.	(32)
J	Carbon Black	Microfil 8	Tests--intersection overlays		87				(44)
NT	Carbon Black			yes					
A	Carbon Black	Microfil 8	Test sections in high speed & traffic	yes	87	88	C	Very tough initially.	(15)
H	Carbon Black		Test sections--ramps, toll plaza with previous rutting and shoving.		86	88	A		
L	Sulfur						F	Not successful in either of 2 projects.	
LB	SEA	Sudic-Pronk	Full Depth Pvmt.	yes	77	81	B	Minor modifications in mixing needed; better resistance to rutting and fatigue on seasonal log-hauling roads.	(22)
Y	SEA		Test overlay	yes	80		C	Mix temp. control needed; not being used by this time.	(25)(26)

MISCELLANEOUS

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
CT	SEA		Commuter parking lots Pavement overlay		81,82 87			Design, testing, placement discussed in report.	(36)(37) (38)(39)
ME	SEA		New construction Overlay		79 81	88	A	Few cracks, smooth ride, but rutting 42% more severe than control.	(40)
ONT	SEA	Gulf Oil, Can.		yes	75 77 78		*	*B (rutting); C (equal or Sl. better crack/skid resistance); constr. problems discussed in papers.	(6)(7)
OH	SEA			yes	80	87		30 sections paved.	(2)
WI	SEA						**	**B (rutting); D (cracking)	(1)
MI	Sulfur Sulphlex							Unsuccessful Unsuccessful	
MAN	Silicone		Antistripping Agent		67			Displaces moisture in hot mix--permits coating of aggregate. In use since 1967.	
VI	Silicone							Used at discretion of contractor.	
NY	Antistripping Agents			yes	76-81		C	Initial, but not long term benefit. Not being used at present.	(27)
CT	Cellulose-Recycled Garbage	Ecofuel	Asphalt extender	yes	80		B	Some musty order. Less cracking. Testing data in report.	(33)

MISCELLANEOUS

AGENCY	GENERIC COMP.	BRAND	USE	CON-TROLS	DATES CONST	DATES EVAL	PERFOR-MANCE	NOTES	REFER-ENCE
NJ	Cement Grout Reinforced Open-graded Bit. concrete	Salviacim	Control severe rutting		87			Performing well (7/88)--previous material had > 1/2" ruts in 3 months.	
LA	SB or AB Latex in Coal Tar		G.A. Airports/slurry seals		78-82				
	Coal Tar		Roadway Slurry Seals					Wheelpath aggregate raveled within nine months.	

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Appendix A. Condition Surveys of Task 4 and 5 Pavements

Project Termini	MP.	Rut Depths[1]	Cracks	Notes
Circle-N F-BRF-HES 25-1(9)0	-reconstruction-			
Galata - E & W RTF 1-4(11)292	303	0.3		Old pavement, rough ride. Extensive transverse and map cracking, some alligator cracking.
Kevin - N IR 15-8(44)380	381 NB	0.25	21	Some longitudinal cracks in shoulder. Transverse cracks very wide and depressed. Some swarms of short transverse and map cracks.
Plains-Paradise F-BRF 6-1(13)96	-total reconstruction-			
Kila - E & W F BRF HES 1-2(37)99	107.8	0.4		Severe alligator cracking; heavily patched; inconsistent rutting; no transverse cracking pattern.
Norris Hill	-reconstruction-			
Wolf Point-E F 1 10(18)593	597	0.3		Cracks too numerous to count. Transverse & map cracks at intervals of 2-10 feet. Longitudinal cr. between wheelpaths.
Bloomfield-N RS 254-1(6)26	STA 1427	0.3	14	Transverse cracks depressed, some alligator and longitudinal cracking.
Custer-'E IR 94-1(49)47	48 EB	0.5	17	Two persistent longitudinal cracks, one in rt. wheel path, driving lane, other in passing lane. May be joints
Helena-W RTF-BRF 8-2(15)34	-reconstruction-			
Potomac-W F-BHF-BRF 24-1(25)9	-reconstruction-			

[1] average of 3 measurements at site ±250 feet. Both lanes on 2 lane roadways, driving lane on Interstate.

APPENDIX B. Task 5 Data.

Bloomfield

	Marshall Stab		% Voids		% AC	
	Center	Edge	Center	Edge	Center	Edge
Site 1	2750	3230	4.5	3.6	5.5	5.8
	3270	1170	4.9	6.9	5.6	5.9
Site 2	3150	1950	4.4	6.3	5.3	6.2
	3380	1930	4.2	5.2	5.8	6.3
Site 3	2670	3190	5.4	4.4	5.9	5.1
	2950	3140	4.8	3.9	5.8	6.5
Site 4	2460	2270	6.0	6.4	6.3	5.6
	2460	2410	5.4	6.0	6.0	5.8
Site 5	2380	1560	5.5	7.3	6.2	6.1
	1670	2070	7.4	6.1	5.7	5.8
Site 6	2950	2940	5.8	7.2	5.4	5.6
	3220	2470	6.1	7.2	5.9	5.9

APPENDIX B.

Custer

	Marshall Stab		% Voids		% AC	
	Center	Edge	Center	Edge	Center	Edge
Site 1	6870	3220	4.4	4.5	5.0	4.8
	7140	--	3.4	7.6	4.7	4.8
Site 2	6230	--	4.2	--	4.9	4.7
	8480	5150	3.5	7.2	5.1	5.0
Site 3	4580	5570	4.7	5.1	4.9	5.1
	--	5590	5.3	7.2	4.9	4.5
Site 4	--	3390	10.9	4.0	5.2	4.8
	2340	5640	9.3	4.4	4.9	5.3
Site 5	--	6010	--	4.4	5.0	4.8
	3200	1750	7.0	5.8	4.9	4.9
Site 6	3680	7630	7.6	3.1	4.8	4.8
	6130	7250	7.7	3.4	5.0	5.4

APPENDIX B.

Helena

	Marshall Stab		% Voids		% AC	
	Center	Edge	Center	Edge	Center	Edge
Site 1	--	4760	9.5	9.4	6.1	6.6
	2600	5170	8.3	8.9	6.3	6.3
Site 2	2150	2190	8.4	14.1	6.1	5.5
	1130	1910	13.9	12.9	6.4	6.3
Site 3	--	--	12.0	8.5	5.5	6.1
	2440	--	12.7	8.3	6.1	6.2
Site 4	2380	--	--	10.8	5.9	6.2
	3490	--	11.3	--	6.2	6.2
Site 5	--	2150	10.4	--	5.6	6.3
	--	--	--	10.0	6.0	6.0
Site 6	2230	--	5.5	9.8	6.3	6.2
	--	--	5.8	8.4	5.8	6.1

APPENDIX B.

Potomac

	Marshall Stab		% Voids		% AC	
	Center	Edge	Center	Edge	Center	Edge
Site 1	4370	4810	8.2	6.1	5.5	5.9
	4450	4150	4.2	5.3	5.7	5.8
Site 2	3030	3510	8.8	8.5	--	4.5
	3660	5540	8.5	5.7	5.7	4.8
Site 3	3220	4070	9.2	6.0	5.2	5.1
	3350	6390	7.5	3.6	5.0	5.3
Site 4	5610	4670	4.1	7.5	5.3	5.7
	5150	4540	5.0	6.8	5.6	5.5
Site 5	2180	2840	10.0	9.5	5.2	4.8
	3920	2620	6.5	8.6	4.6	5.2
Site 6	2830	2570	9.1	9.1	5.6	5.2
	2220	2100	9.8	9.8	4.9	4.9

Aggregate Gradations -- % Retained

Bloomfield

	3/4"	1/2"	3/8"	10M	40M	80M	200M	-200M
Site 1	2.9	17.4	33.3	13.4	13.7	8.8	5.1	5.3
	5.0	12.4	30.0	16.2	15.5	9.2	5.3	6.2
	4.2	15.2	32.8	14.3	14.2	9.3	5.2	4.7
	2.9	13.8	30.6	15.7	16.3	9.7	5.5	5.5
Site 2	5.2	15.5	33.9	16.7	11.3	7.2	4.8	5.3
	1.8	12.8	32.0	17.7	16.2	8.6	5.5	5.4
	1.9	18.6	31.6	14.9	13.9	8.2	5.2	5.6
	3.0	10.8	29.8	18.3	17.6	9.2	5.6	5.6
Site 3	3.2	17.5	28.5	15.6	15.2	9.1	5.6	5.4
	5.2	16.9	29.6	15.0	14.1	8.8	5.2	5.1
	3.2	16.4	28.7	16.4	15.4	8.6	5.4	5.8
	5.1	14.4	32.8	13.9	14.3	8.6	5.5	5.2
Site 4	0.7	13.3	31.4	17.8	16.6	8.5	6.1	5.6
	3.3	16.9	34.4	14.2	12.3	6.8	5.3	6.4
	2.2	13.9	32.8	16.8	14.4	7.6	5.7	6.6
	3.3	18.9	29.5	15.3	13.6	7.0	5.3	7.1
Site 5	2.4	12.3	30.8	17.5	15.8	8.7	6.1	6.5
	2.5	14.7	28.6	16.9	16.0	8.4	5.8	7.0
	3.8	17.5	31.5	14.5	13.3	8.0	5.7	5.7
	2.7	17.5	30.2	16.0	14.1	8.0	5.7	5.8
Site 6	3.0	15.5	36.6	14.7	12.6	6.8	5.2	5.7
	1.7	15.0	33.2	16.5	14.9	7.3	5.6	5.8
	0.9	14.9	31.1	18.0	15.7	7.8	5.9	5.5
	0.8	12.9	33.8	17.4	15.7	7.6	5.9	5.8

Aggregate Gradations -- % Retained

Custer

	3/4"	1/2"	3/8"	10M	40M	80M	200M	-200M
Site 1	13.4	14.4	18.8	15.7	16.7	9.1	5.9	6.0
	17.3	13.8	18.9	14.6	15.4	8.5	5.6	5.8
	18.8	15.8	16.9	13.7	14.9	8.4	5.6	5.8
	15.9	17.3	16.4	15.0	15.4	8.7	57	5.5
Site 2	16.5	16.1	14.6	15.7	16.3	9.1	5.7	6.0
	15.1	17.3	18.0	15.2	15.0	8.5	5.3	5.5
	12.2	13.4	20.5	16.0	16.5	9.3	5.9	6.3
	14.1	13.9	19.2	15.4	16.4	9.1	5.7	6.2
Site 3	13.5	16.8	17.8	14.6	15.3	9.3	6.3	6.3
	11.1	14.0	18.5	16.8	16.6	10.0	6.6	6.3
	12.8	14.6	19.7	15.2	15.5	9.5	6.3	6.4
	17.6	15.8	19.4	13.6	13.5	8.4	5.7	5.9
Site 4	16.5	20.3	18.6	13.2	13.1	7.5	5.2	5.5
	13.7	16.9	18.8	15.8	14.8	8.1	5.6	6.2
	12.1	17.0	20.6	14.6	15.0	8.3	5.6	6.7
	13.1	16.4	19.1	15.5	15.9	8.3	5.7	5.9
Site 5	12.3	16.8	19.4	15.1	15.0	8.9	6.0	6.5
	16.3	16.4	17.0	14.9	14.8	8.7	5.7	6.2
	14.7	16.3	17.0	15.7	15.2	8.9	6.0	6.1
	16.5	13.4	17.8	16.0	15.3	8.9	5.9	6.3
Site 6	18.3	17.5	16.8	12.2	14.5	9.2	5.7	5.8
	16.2	13.9	17.0	16.8	15.6	8.8	5.7	5.8
	14.8	14.6	17.3	15.9	16.1	9.3	5.9	6.0
	9.0	11.2	20.1	19.2	18.0	9.8	6.0	6.6

Aggregate Gradations -- % Retained

Helena

	3/4"	1/2"	3/8"	10M	40M	80M	200M	-200M
Site 1	13.3	10.8	19.9	13.8	24.9	8.1	4.2	5.0
	8.7	10.1	17.1	16.9	28.6	8.7	4.4	5.4
	10.6	10.9	19.8	15.3	25.8	8.2	4.3	4.9
	13.9	7.4	18.7	15.2	27.4	8.4	4.2	4.8
Site 2	9.7	10.7	19.8	16.4	26.6	8.0	4.1	4.7
	17.7	13.5	20.6	12.5	20.4	7.1	3.7	4.4
	11.7	9.7	18.8	16.3	26.4	8.0	4.0	4.9
	11.1	9.8	19.0	16.6	26.4	8.2	4.1	4.8
Site 3	12.0	16.5	21.6	12.9	21.0	7.2	3.6	5.3
	11.5	10.9	19.1	15.6	25.9	8.0	3.9	5.0
	9.6	11.6	21.9	14.5	25.5	8.1	4.0	4.8
	9.1	11.4	19.6	15.8	26.1	8.2	4.1	5.6
Site 4	15.0	11.2	19.4	14.3	24.4	7.8	3.8	4.1
	9.3	8.4	20.8	17.1	27.2	8.2	4.1	4.8
Site 5	12.3	13.5	22.8	14.4	21.7	7.3	3.9	4.2
	7.6	10.4	22.4	17.0	25.9	8.0	4.0	4.9
	12.6	11.9	18.6	15.5	24.6	7.8	4.1	4.9
	9.9	14.4	19.0	15.5	24.9	7.7	4.0	4.5
Site 6	9.5	8.4	21.6	17.1	26.7	7.9	3.9	4.9
	7.2	12.8	21.0	15.7	26.4	7.9	4.0	4.8
	11.9	13.3	19.8	15.5	23.8	7.3	3.8	4.6
	10.7	10.2	22.2	16.1	24.7	7.6	3.9	4.6

Aggregate Gradations -- % Retained

Potomac

	3/4"	1/2"	3/8"	10M	40M	80M	200M	-200M
Site 1	19.0	13.5	18.3	15.9	16.9	6.1	3.8	6.6
	17.8	11.1	17.8	16.8	18.3	6.6	4.1	7.2
	17.3	12.2	18.0	17.5	17.1	6.2	4.1	7.6
	18.7	12.7	19.6	15.2	16.8	6.2	4.0	6.7
Site 2	23.0	18.6	19.2	12.0	12.3	5.2	3.4	6.2
	17.8	11.4	23.3	15.3	15.6	6.1	3.9	6.6
	22.3	13.9	18.0	14.4	14.8	6.2	3.9	6.5
	20.3	13.0	19.1	14.7	16.4	6.4	4.1	6.1
Site 3	19.5	13.0	21.1	15.0	14.7	6.0	4.0	6.6
	18.3	16.0	20.8	13.9	14.4	5.8	3.8	6.9
	15.9	15.5	22.6	14.7	14.6	5.9	3.8	6.9
	15.3	15.3	22.2	15.0	14.9	5.9	4.0	7.4
Site 4	13.2	11.4	21.5	16.8	18.2	7.2	4.3	7.4
	13.3	13.2	20.2	16.6	18.2	7.1	4.3	7.1
	9.8	15.0	23.0	16.3	17.4	6.8	4.3	7.4
	15.4	15.1	20.8	15.1	16.2	6.5	4.0	6.8
Site 5	24.1	17.2	15.3	13.2	14.3	6.1	3.7	6.0
	27.7	12.9	16.9	13.1	13.6	5.9	3.6	6.2
	20.1	14.5	16.7	15.3	16.2	6.7	4.0	6.5
	19.8	11.8	17.1	16.2	17.3	6.8	4.1	6.9
Site 6	19.5	14.3	20.2	14.6	15.4	6.2	3.7	6.1
	19.5	15.8	18.9	14.4	14.7	6.1	3.8	6.7
	20.9	15.7	19.7	13.7	14.3	6.0	3.7	6.0
	19.3	13.7	20.9	14.3	15.0	6.2	3.8	6.7

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